PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
B01D 61/06, 63/12, 61/08

A1

(11) International Publication Number: WO 98/23361

(43) International Publication Date: 4 June 1998 (04.06.98)

(21) International Application Number: PCT/CA97/00901

(22) International Filing Date: 24 November 1997 (24.11.97)

(30) Priority Data:
60/031,492 26 November 1996 (26.11.96) US

(71)(72) Applicant and Inventor: KEEFER, Bowie, Gordon [CA/CA]; 4324 West 11th Avenue, Vancouver, British Columbia V6R 2M1 (CA).

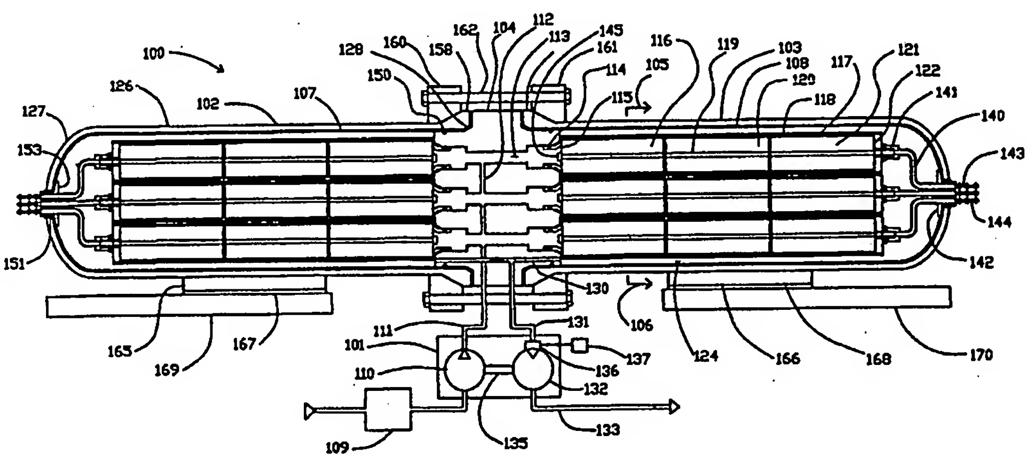
(72) Inventor: DOMAN, David, George; 927 Bayview Drive, Delta, British Columbia V4M 2R5 (CA).

(81) Designated States: AU, CA, IL, JP, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published

With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: APPARATUS AND METHOD FOR REVERSE OSMOSIS DESALINATION



(57) Abstract

Each module (100) of a modular reverse osmosis apparatus comprises a pressure vessel (102, 103) containing a plurality of membrane elements (116) installed to receive pressurized feed flow in parallel and in series, and a free rotor energy recovery booster pump (101) delivering the feed flow to that vessel (102, 103). The free rotor energy recovery booster pump (101) of each module (100) is powered by the reject flow exiting the pressure vessel (102, 103) of that module (100), to boost the feed pressure from an initial feed supply pressure to the much higher working pressure of the membrane elements (116). The invention further provides means for simplified fluid sealing, installation, and performance monitoring of membrane elements (116) within the pressure vessel (102, 103) of each module (100) in contemplated large scale reverse osmosis desalination plants. In larger plants, a plurality of modules are supplied in parallel with feed from a common feed manifold, pressurized to the feed supply pressure by a single feed pump, in turn powered for example by a steam or gas turbine so as to provide improved economies of scale and lower energy costs for desalination. Independently of the use of free rotor booster pumps or alternative hydraulic machinery, the invention provides improved membrane brine sealing configurations and improved large diameter pressure vessels for bundles of spiral wound membrane elements.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

APPARATUS AND METHOD FOR REVERSE OSMOSIS DESALINATION

TECHNICAL FIELD

Reverse osmosis has become widely accepted for water desalination, dominating smaller scale sea water desalting applications and competing strongly with thermal desalination processes in medium scale applications in the range of several thousand cubic metres per day product water capacity. Thermal processes continue to dominate the largest scale applications.

With membrane performance and reliability increasingly consolidated as high performance membranes attain technological and manufacturing quality control maturity, while successful field experience is ever more consistently obtained with good pretreatment practices, single stage reverse osmosis might be expected to obtain wider acceptance for large scale sea water desalting.

However, the wider penetration of prior art reverse osmosis technology in larger scale applications has been inhibited by the much more favourable economies of scale for thermal desalination equipment, the ability of thermal desalination plants to consume low grade heat rejected by thermal power plants, and the availability of low cost fuels in petroleum exporting regions where much of the present desalination market is concentrated.

Advances in the art of membrane technology and manufacturing, and in the practice of effective feed water pretreatment, have not been adequately matched by improvements in the mechanical and pressure containment aspects of reverse osmosis technology. The present invention addresses the need for process simplifications and apparatus improvements in the high pressure section of reverse osmosis plant, to reduce capital and operating costs with much enhanced economies of scale.

Economies of scale are readily available to thermal desalting processes, reflecting the economical scale-up of heat exchange equipment. Such favourable economies of scale have been denied to reverse osmosis, whose basic building blocks have been the membrane elements and the membrane pressure vessels containing one or a few membrane elements. Each conventional membrane pressure vessel has a relatively small flow rating, up to roughly 100 m^3/day product capacity. The capacity ratings of the high pressure feed pumps, motors and energy recovery turbines are then constrained by the number of membrane pressure housings which may economically be manifolded in parallel. This constraint in the largest capacity ratings of the hydraulic machinery and prime movers further limits economies of scale for the largest desalting plants.

The membrane pressure vessels are installed in racks, with their feed and reject brine ports connected in parallel to high pressure feed and reject manifolds. The complexity of pipe manifolds, subject to full working pressure of corrosive sea water or reject brine with satisfactory flow distribution to all membrane pressure vessels in parallel, and the cost of high alloy corrosion resistant piping, limits the practicable number of membrane pressure vessels in a single high pressure process train, fed typically by a single high pressure pump with electric motor drive assisted by an energy recovery turbine powered by the reject brine.

The low packing density of the membranes, installed in separate pressure vessels on racks, results in long pipe runs of excessive cost and excessive pressure drop along with flow distribution difficulties, unless the number of membrane elements fed by a single pump is relatively small.

Since the process train fed by a single high pressure pump has therefore been constrained to relatively small flow ratings, the efficiencies of the pumping and energy recovery

turbine machinery are penalized. Also, the prime mover of the feed pump is relatively small. Hence, very large plants would have large numbers of relatively small trains in parallel, and economic and efficiency economies of scale are unobtainable. Since electric motors are more suitable than combustion or steam turbines for small power ratings, opportunities for direct integration of reverse osmosis plants with thermal power plants have been inhibited. Consequently, reverse osmosis has been unable to compete with distillation for very large installations where energy would be generated from fossil fuel combustion.

In larger conventional reverse osmosis plants, the capital cost allocations associated with pressure generation (prime movers, high pressure pumps and turbines) and with pressure containment (membrane pressure vessels, high pressure manifolds and piping) are each significantly greater than the cost of the bare membrane elements. The present invention is directed toward reducing the costs of pressure generation and pressure containment, especially for the largest desalting capacities.

A conventional membrane pressure vessel typically contains one or two hollow fibre bundles, or a string of up to typically six spiral wrap elements, in a cylindrical filament wound FRP shell whose inside diameter corresponds to the outside diameter of the membrane elements. Pressure vessel end closures are provided by full diameter plugs, with the axial pressure loads transmitted to the FRP shell in shear, typically by snap ring or segmented ring retainers in machined grooves. The end closure configurations are structurally inefficient, and result in some congestion of piping connections for feed, brine and product.

Particularly for spiral wrap membrane elements, brine seals are required to prevent bypass of feed around the element. Prior art brine seals form a fluid seal between each membrane element and the inner wall of the pressure vessel.

When a string of several elements is installed end-to-end in a single pressure vessel, a considerable axial force is necessary to overcome the frictional resistance of the brine seals against the vessel wall. The string of elements must be installed from one end of the vessel, while both ends of the vessel must be opened to enable removal of the elements by pushing them through.

Some prior art inventors have explored some approaches toward installing greater numbers of membrane elements in a single pressure vessel of greater diameter. Call (U.S. Patent No. 4,083,780) installs parallel bundled spiral wrap elements, having conventional full diameter brine seals sealing each element against feed to brine bypass within tubular support sleeves in a cylindrical vessel having feed and reject connections at opposite ends, with each support sleeve containing several elements concentrating the feed in series, and with full diameter end closures. Schmitt et al (U.S. Patent No. 4,476,015) disclose another configuration for installing a parallel bundle of spiral wrap elements multistage reverse osmosis systems, the bundle being limited to a single element axial length, and with the feed concentrated successively by separate groups of the membrane elements. The Schmitt et al invention enables compact packaging of relative small reverse osmosis plants, but cannot be used for large plant modules. Each of these prior inventions has relatively complex brine sealing arrangements, and has full diameter pressure vessel end closures at both ends.

The high cost of full diameter flanges and heads for large diameter pressure vessels, together with handling equipment for opening the heavy full diameter heads, would nullify cost savings from simplification of high pressure pipe connections. Full diameter end closures at both ends of large diameter vessels would also preclude construction from fibre reinforced plastic which has proven very satisfactory for conventional smaller diameter membrane vessels. Prior

art approaches to bundling membrane elements in large diameter pressure vessels have thus proved uneconomic.

The present invention is extended from previous work on free rotor energy recovery booster pumps [Keefer (U.S. Patent No. 4,973,408)] for application in reverse osmosis desalination plants. Such pumps provide energy recovery by applying the pressure energy of the concentrate fluid to power the boost pump in raising the pressure of the feed fluid from an initial feed pressure to the working pressure of the membranes. In preferred embodiments, the booster pump is a single stage centrifugal pump on a common shaft with a radial turbine or Pelton turbine which is the sole mechanical power source to the booster pump. Booster pumps of this type have been commercially developed with further improvements by Oklejas et al (U.S. Patents Nos. 4,966,708; 4,983,305 and 5,049,045). Alternatively, the booster pump may be a single stage or multistage centrifugal pump driven by a Pelton turbine.

As emphasized in U.S. Patent No. 4,973,408 and verified by operating experience [E. Oklejas and B. Keefer, "The Hydraulic TurboCharger™ for Reverse Osmosis: Operating Characteristics", Proceedings, World Desalination Conference, Washington, D.C., 1991], the free rotor booster pump provides important advantages of control simplification, and in reducing or eliminating throttling losses in auxiliary control valves, through the important degree of passive self-regulation and self-starting characteristics inherent to free rotor booster pumps. The freedom of the free rotor booster pump to select its own shaft speed, responding to changing membrane flux response to applied pressure and the pressure/flow characteristic of the feed supply means, helps to accommodate any mismatch between the feed supply source (e.g. a low pressure centrifugal pump) so as to minimize undesirable variations of pressure and flow at any setting of the turbine nozzle.

The present invention provides an improved modular approach to larger scale reverse osmosis plants, with the objects of improved economies of scale, improved energy efficiency, control simplicity, simplified maintenance, and enhanced operating flexibility for responding to changes in product demand or for isolating portions of the plant undergoing maintenance. The invention further enables the use of very large capacity feed pumps, optionally powered by gas or steam turbines, to reduce overall capital and operating cost of the largest scale desalination plants.

DISCLOSURE OF INVENTION

Each module of a modular reverse osmosis apparatus comprises (1) a pressure vessel containing a plurality of membrane elements installed to receive pressurized feed flow in parallel and in series, and (2) a free rotor energy recovery booster pump delivering the feed flow at the membrane working pressure to that vessel. The free rotor booster pump is preferably close-coupled to the pressure vessel so as to minimize the need for high pressure piping. Alternatively, a module may be defined with the free rotor booster pump coupled in parallel to two or more pressure vessels.

Close-coupling of the free rotor booster pump to the pressure vessel also increases energy efficiency by reducing high pressure loop pressure drop due to flow friction in piping. This aspect of the invention is important, since the power output of a concentrate energy recovery turbine is very sensitive to pressure drop losses in the high pressure loop. Such pressure drops are higher in conventional reverse osmosis plants with extensive pipe connections and congested pressure vessel ports in the high pressure loop between feed and concentrate.

The free rotor energy recovery booster pump of each module

is powered by the reject flow exiting the pressure vessel of that module, to boost the feed pressure from an initial feed supply pressure supplied by appropriate feed supply means to the much higher working pressure of the membrane elements.

The invention provides means for simplified installation, performance monitoring and fluid sealing of membrane elements within the pressure vessel of each module in contemplated large scale reverse osmosis desalination plants.

Multiple modules according to the invention may be supplied in parallel with feed from a single feed supply means. The booster pumps of the modules then receive feed from a common feed manifold, pressurized to the feed supply pressure by a single feed pump or alternatively by a number of feed pumps. The feed pump is in turn powered by a single prime mover which may be a fixed or variable speed electric motor, or a steam or gas turbine, so as to provide improved economies of scale, simplified control and lower power cost for larger scale desalination.

With multiple modules in a plant fed from a single feed supply means, one module may be removed from service for maintenance, such as membrane replacement or cleaning, without shutting down the plant. With multiple feed pumps in the feed supply means, one pump may be removed from service without shutting down the plant or any of the modules normally fed by that pump. The number of modules need not be equal to the number of feed pumps, and the capacity ratings of modules and feed pumps may be separately optimized. The use of very large capacity feed pumps for larger scale plants is thus made possible, in turn facilitating the option of using relatively low cost gas turbine prime movers compared to electric motor prime movers and external power generation plant.

Use of inherently variable speed prime movers will facilitate satisfactory operation and control of the plant, especially when either the number of operational modules receiving feed fluid from the feed supply means, or the number of operational feed pumps comprising that feed supply means, is changed in order to vary total permeate delivery in response to changing demand or else to allow maintenance of modules or feed pumps removed from service.

In preferred embodiments using spiral wrap membrane elements, several membrane elements may be connected end to end to form a membrane string. A plurality of membrane strings are installed in parallel honeycomb array to form a membrane string bundle within a cylindrical portion of the pressure vessel. The membrane string bundle fits within the full diameter defined by the inner wall of the vessel.

In a vertically oriented pressure vessel, membrane strings may be loaded individually through an access hatch at the top of the vessel. The access hatch may have a diameter much smaller than the diameter of the cylindrical portion of the vessel, thus enabling much lower capital cost of the vessel compared to use of full diameter end closures and flanges. Feed entry and concentrate discharge connections from the pressure vessel to the free rotor booster pump, and permeate delivery connections from a permeate collection manifold, may then conveniently exit the lower end of the vessel.

In a horizontally oriented pressure vessel, the membrane strings may be formed by loading individual membrane elements into a support tube within the vessel for each string. The support tubes themselves are supported in parallel alignment with respect to the inner wall of a cylindrical portion of the pressure vessel. Alternatively, the support tubes may be attached together and loaded with membrane elements to form a membrane bundle, which may be installed and removed from the vessel as a single assembly.

Preferably, brine seals between membrane elements of a string will be achieved by sealing between the ends of adjacent elements, rather than between each element and the vessel. Frictional resistance of installing the membrane string is thus minimized. A tensile connection would be provided between the membrane elements of a string, so that the string may be installed from one end of the vessel and subsequently removed from the same end with no need to open the other end for disassembly.

Some illustrative horizontally oriented configurations have two axially separated membrane bundles in each pressure vessel assembly. The pressure vessel assembly may then comprise two cylindrical pressure shells or half vessels, clamped and sealed to a full diameter vessel connector. The vessel connector provides a common bulkhead for the half vessels, from which feed entry and concentrate discharge connections communicate to the free rotor booster pump. Each half vessel has a full diameter opening at one end for its sealing connection to the vessel connector, but has a closed head with at most a reduced diameter opening for fluid connections at the other end. The half vessels may be mounted on sliding skid ways, so that they may be retracted from the vessel connector for access in order to replace membrane elements. This approach also reduces pressure vessel costs, by requiring a full diameter opening only at one end of each pressure shell, and then by doubling the attainable volume for given diameter of the combined vessel by connecting two half vessels each containing a bundle of full length membrane strings.

The invention enables rapid and convenient replacement of membrane elements, in alternative configurations as separate elements, strings or bundles, when the module is withdrawn from services and the pressure vessel opened for such replacement. The invention also provides means for testing permeate quality from each membrane string, and for shutting off permeate flow from any defective string within a module,

while the module may remain in uninterrupted operation with one or several of its membrane strings thus isolated and shut down.

In general, a reverse osmosis plant according to the invention will have one process train or multiple process trains in parallel, with each train being defined by a single high pressure feed pump with its prime mover. Each train comprises at least one module and more usually multiple modules in parallel. Each module has a number "M" of (at least one) membrane strings in the pressure vessel(s) cooperating typically with a single free rotor booster pump.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a simplified schematic of a reverse osmosis plant with gas turbine prime movers each powering a plurality of modules according to the invention.

Fig. 2 shows an integrated reverse osmosis module according to the invention, with the pressure vessel and membrane elements oriented horizontally, and with two bundles of membrane elements strings in separate pressure housing shells.

Fig. 3 shows a cross section view of the module of Fig. 2.

Fig. 4 shows a module similar to that of Fig. 2, but with the permeate delivery conduits manifolded in a connector between the two pressure housing shells.

Fig. 5 shows a module similar to that of Fig. 2, but with the feed and concentrate fluid connections at the end of one of the two pressure housing shells.

Fig. 6 shows a module similar to that of Fig. 5, but with only one vessel.

Fig. 7 shows an integrated reverse osmosis module according to the invention, with the pressure vessel and membrane elements oriented vertically.

Fig. 8 shows a cross section view across the membrane element strings in the module of Fig. 7.

Fig. 9 shows a cross section view across the permeate and brine collection manifolds in the module of Fig. 7.

Fig. 10 shows a membrane element string.

Figs. 11 and 12 show alternative brine seals for the

membrane element string of Fig. 10.

Fig. 13 shows a pilot-operated shutoff valve for detecting and isolating defective membrane element strings in the module of Fig. 7.

Fig. 14 shows a 5 million gallon (approximately 19,000 m^3) per day reverse osmosis sea water desalination train.

Fig. 15 shows a 50 million gallon (approximately 190,000 m^3) per day reverse osmosis sea water desalination train.

Fig. 16 shows a 75 million gallon (approximately 284,000 m^3) per day reverse osmosis sea water desalination plant with five trains.

MODES FOR CARRYING OUT THE INVENTION

Fig. 1

A reverse osmosis plant 1 includes two parallel process trains 2 and 3, so that $N_T = 2$. Feed water is drawn from intake 4 by a low pressure intake pump 5, and delivered to pretreatment plant 6. Pretreatment typically includes filtration, sterilization and pH adjustment of the feed water. The pretreated feed water is then delivered at a low pressure by supply conduits 7 and 8 to the pressure feed pumps 9 and 10 for each of trains 2 and 3. The feed pumps raise the feed water pressure to a feed supply pressure.

For sea water desalination by single stage reverse osmosis, the working pressure of the membranes will be a high pressure in the typical range of 5.5 to 8 MPa. In the present invention, the feed supply pressure is a medium pressure of the order of half the membrane working pressure. Free rotor booster pumps will recover energy from the reject brine exiting the membranes at approximately the working pressure, in order to boost the pressure of the feed from the feed supply pressure to the working pressure.

Feed pumps 9 and 10 are driven respectively by prime movers 11 and 12 through drive shafts 13 and 14. The prime movers may be gas or steam turbines, electric motors or diesel engines. For a large plant in a region supplied with natural gas, the prime movers may preferably be gas turbines driving the feed pumps directly. For a large desalination plant operated in conjunction with a nuclear power plant or a coal combustion power plant, the prime movers may preferably be steam turbines. With large capacity feed pumps, direct turbine drive provides important cost savings through elimination of electrical power conversion steps, lower pump cost because of high shaft speed, and higher efficiency.

In process train 2, feed water pressurized to the feed

supply pressure by feed pump 9 enters medium pressure supply manifold 20, which feeds a set of four modules in parallel. A module is here defined by a free motor booster pump 21 cooperating with a single pressure vessel 22 containing all the membrane elements 23 within that module.

In a module of train 2, feed water is drawn from manifold 20 by a medium pressure feed conduit 24. A normally open shutoff valve 25 in conduit 24 is provided as an isolation valve. Valve 25 is closed to isolate and depressurize this module whenever it is removed from service for maintenance, while the rest of the plant continues operating. The feed water is conveyed by conduit 24 to pump 26 of the free rotor booster pump, which raises its pressure from the feed supply pressure to the membrane working pressure. Within the free rotor booster pump 21, pump 26 is driven by turbine 27 coupled by shaft 28.

The membranes 23 separate the feed water into a purified permeate stream delivered at low pressure from vessel 22 to product delivery manifold 30, and a concentrate stream delivered at substantially the membrane working pressure (less the pressure drop of flow friction in the membrane brine channels) by concentrate discharge connection 32 to the inlet nozzle 33 of turbine 27. Turbine 27 expands the concentrate fluid to substantially atmospheric pressure for discharge through exhaust manifold 34. The other three modules of train 2 are similarly defined by free rotor booster pumps 35, 36 and 37 respectively cooperating with membrane pressure vessels 38, 39 and 40.

In process train 3, feed water pressurized to the feed supply pressure by feed pump 10 enters medium pressure supply manifold 42, which in this illustrative embodiment feeds a set of two modules in parallel. A module is here defined by a free motor booster pump 43 cooperating with a plurality of two pressure vessels 44 and 45 containing all the membrane elements 46 and 47 of that module. Permeate

fluid is delivered by product delivery manifold 48, while exhaust fluid is discharged by exhaust manifold 49.

Normally open shutoff valves 50 and 51 are isolation valves, which may be closed to isolate either of feed pumps 9 or 10 respectively from its medium pressure supply manifolds 20 or 42, while cross-over valve 53 may be opened so that modules in train 2 or 3 may be supplied with feed flow from feed pumps 10 or 9 from the opposite train 3 or 2. Hence, the present invention enables continued operation of modules when other modules or feed pumps (or feed pump prime movers) are withdrawn from service for scheduled or unscheduled maintenance. Maximum plant availability is thus achieved.

Figs. 2 and 3

A module 100 according to the invention is shown in Fig. 2. Module 100 is defined by free rotor booster pump 101 cooperating with horizontal pressure shells or half vessels 102 and 103, which are coupled together by full diameter vessel connector 104. Fig. 3 is a section of half vessel 103 as indicated by arrows 105 and 106. Half vessels 102 and 103 have internal liners 107 and 108 respectively. Half vessels 102 and 102 combined with vessel connector 104 provide a pressure vessel assembly for the module.

Feed water at the feed supply pressure is delivered to pump 110 of free rotor booster pump 101 by feed supply means 109. Pump 110 delivers the feed water pressurized to the membrane working pressure by feed entry connection 111 to feed gallery 112 in connector 104. Feed water from gallery 112 is introduced by a set of conduits 113 and brine connector 114 to brine channel entrance 115 of the first membrane element 116 of a string 117 of membrane elements contained within support tube 118. The feed water contacts the membrane surfaces in the brine channels of the elements, and is concentrated by withdrawal of permeate through the

membranes.

Suitable membrane elements for the invention include preferably spiral wrap membrane elements, and alternatively hollow fiber elements in special configurations such as disclosed by Eckman in U.S. Patent No. 5,470,469. As illustrated in Fig. 10, suitable spiral wrap membrane elements have a circular cylindrical body whose axis extends between the two ends of the element, so that pressurized feed fluid is admitted to one end of the element to contact the membranes and to be concentrated in the brine channels of the element, pressurized concentrate fluid or brine is delivered from the other end of the element, and permeate fluid is delivered at low pressure from a product tube extending along the axis of the element.

A string of membrane elements is here defined as a set of elements installed in line along their common axis, in series for feed flow, and in parallel for permeate delivery through their directly interconnected product tubes 119. The number "L" of elements in a string may be any number from 1 to about 6 or 7. The number "M" of strings is the sum of the number of strings in each vessel of the module. The total number "N" of membrane elements in the module is the product N = M X L. In this example M = 2 X 7 = 14.

The membrane element string in a support tube 118 is depicted as including a first element 116, an intermediate element 120, and a last element 121; so that L = 3, and N = M X L = 14 X 3 = 42. This number of elements per string is here chosen for simplicity of illustrating the invention. Preferably, the number of elements per string would be as large as practicable to minimize pressure vessel costs, for example L = 6 with four intermediate elements between the first and last elements of the string.

The feed enters the brine channel entrance 115 of first element 116, and the concentrate exits from brine channel

exit 122 of last element 121.

As shown in Fig. 3, the support tubes 118 are installed in a hexagonal array in vessel 103, with a void volume 124 between the membrane strings and the pressure vessel wall. The support tubes may be attached to each other by adhesive bonded spacer pads 125, or may be secured by light transverse bulkheads. The membrane strings within the support tubes form a hexagonally packed bundle. The interstitial voids between the membrane strings, and the void volume between the bundle and the vessel wall, provide a useful flow path for pressurized fluid counter to pressurized fluid flow through the brine channels of the membrane strings, so that feed entry and concentrate discharge connections may both be made to one end of the vessel.

Half vessel 102 has a cylindrical portion 126 with an internal diameter, in which the hexagonally packed bundle of membrane strings in support tubes is installed with the axis of each membrane string parallel to the horizontal axis of cylindrical vessel portion 126. Half vessel 102 has a closed or reduced diameter head 127 at a first end 127 of cylindrical portion 126. In embodiment 100, head 127 has a reduced diameter penetration for plug 153 with permeate delivery connections. Half vessel 102 has a full diameter opening at second end 128 of cylindrical portion 126, and is flanged to vessel connector 104 at second end 128.

Concentrate fluid flowing from brine channel exit 122 enters the internal volume of vessel 103 (or vessel 102). The concentrate fluid flows in the interstitial voids 124 between the support tubes to enter conduit 130 in connector 104, and thence by concentrate discharge connection 131 to turbine 132 of free rotor booster pump 101. Turbine 132 expands the concentrate fluid from its pressure of substantially the working pressure (less frictional pressure

drops in the brine channel and conduits) to substantially atmospheric pressure, at which the concentrate fluid is discharged by exhaust conduit 133.

Turbine 132 directly drives pump 110 by shaft 135, and is the only mechanical power source to pump 110. Turbine 132 may be a radial inflow turbine, similar to a reverse running centrifugal pump; or alternatively a Pelton turbine. The turbine 132 may be fitted with an adjustable nozzle 136, as commonly used in Pelton turbines to adjust the nozzle cross-sectional area to achieve the most efficient flow velocity under desired flow and pressure operating conditions. Nozzle 136 is adjusted by actuator 137.

Permeate fluid is withdrawn at low pressure from product tube 119 of each membrane string, entering delivery conduit 140 through product tube connector 141. The permeate delivery conduits 140 from the membrane strings exit the vessel 103 through plug 142, and serve as permeate delivery connections. A shutoff valve 143 and sample port may be provided on each delivery conduit 140 immediately outside plug 142. The permeate is then delivered by flexible hose connections 144. The opposite end of product tube 119 from product tube connector 141 is closed by plug 145.

If the permeate quality from any membrane string should become unacceptable due to membrane failure or a static seal failure, that defective membrane string may be isolated by closing the corresponding shutoff valve 143. The module may then continue in operation with no permeate delivery from the defective string, until a conveniently scheduled shutdown for membrane or seal replacement.

Half vessels 102 and 103 may be fabricated from carbon steel, in which case liners 107 and 108 must be made of a corrosion-resistant material. The liners may be provided as integral cladding or a separate liner of stainless steel or titanium, or alternatively may be formed from a

thermoplastic or elastomeric material. Static seals 150 and 151 are provided to seal the pressure vessel 102 to connector 104 and to plug 153 respectively.

The liner 108 shown in Fig. 3 may be fabricated from a thermoplastic material, serving as a corrosion protection jacket for vessel 103. The liner is depicted with spacer ribs 155 defining fluid filled voids 156 for corrosion isolation between the liner and the inner wall 157 of vessel 103. Voids 156 intercommunicate with each other, and are filled with a noncorrosive liquid. A diaphragm 158 enclosing a reservoir 159 of the noncorrosive liquid is provided for pressure equalization between the voids 156 and the concentrate fluid in voids 124.

Alternatively, half vessels 102 and 103 may be fabricated from fiber reinforced plastic (e.g. filament wound epoxy glass), in which case liners 107 and 108 may be a thermoplastic layer formed on the filament winding mandrel.

Half vessels 102 and 103 have external flanges 158 and 159, respectively engaging clamping collars 160 and 161 which are retained by tie bolts 162. To open the vessels for servicing and replacement of membrane elements, means are provided to move the half vessels from the vessel connector. Half vessels 102 and 103 are mounted on cradles 165 and 166, respectively sliding with linear bearing pads 167 and 168 on fixed slides or rails 169 and 170, so that each half vessel can be moved apart from the vessel connector for access. Once separated and cleared from the vessel connector, a half vessel may be moved further back axially, or moved laterally, or else slewed through an angle in the horizontal plane so as to provide access for membrane element inspection, removal and replacement. Half vessels 102 and 103 have heads 172 and 173 respectively, at their opposite ends from flanges 160 and 159. Since the openings at flanges 159 and 160 are full diameter, all vessel internals may be installed and serviced through those openings. In

this embodiment, reduced diameter plugs 142 and 153 penetrate heads 173 and 172 respectively. The external flanges 159 and 160 define the open ends of the half vessels, while heads 172 and 173 define the closed ends of half vessels 102 and 103.

Fig. 4

Embodiment 200 is similar to embodiment 100, but with provision to deliver the permeate fluid from connector 104, and with the opposite direction of feed flow in the membrane strings.

Pressurized feed fluid is delivered from free rotor pump 101 by feed entry connection 111 to connector 104, and thence to conduits 201 and 202 communicating to the interiors 203 and 204 of vessels 102 and 103. The feed enters the brine channel entrance 206 of first element 207. The feed then flows while being concentrated through intermediate element 208, and the concentrate exits from last element 209 through brine channel exit 210 into brine connector 114. The concentrate then flows though conduit 211 to brine manifold 212, which communicates by concentrate discharge connection 131 to turbine 132.

Permeate fluid is withdrawn at low pressure from product tube 119 of each membrane string, entering permeate delivery connection 214 through conduit 215 and product tube connector 216. The permeate delivery connections 214 from the membrane strings are conduits exiting the vessel connector 104 to shutoff isolation valve 220 immediately outside connector 104. The product tubes 119 and 221 of coaxially opposed pairs of membrane strings in vessels 102 and 103 may be connected to a common permeate delivery connection 214 as shown. Product tubes 119 are closed at their opposite end from product tube connector 216 by plug 223. In this embodiment, no penetrations are required

through heads 172 and 172, and half vessels 102 and 103 may be separated from connector 104 to provide access for membrane replacement, without disturbing any of the feed, concentrate and permeate fluid connections to the pressure vessel assembly.

Fig. 5

In embodiment 230, the free rotor booster pump 101 is mounted adjacent the head 231 of vessel 102. Feed fluid is delivered from pump 110 through feed entry connection 111 to annular channel 232 and thence to the interior 203 of vessel 102. Vessel 102 is connected to vessel 103 by full diameter vessel connector 235 with static seals 236. Vessel connector 235 is here a cylindrical sleeve.

A concentrate fluid collection zone 237 is defined by bulkheads 238 and 239 adjacent sleeve 235 in vessels 102 and 103 respectively. Conduit 240, or preferably a plurality of conduits 240, provides fluid communication between vessel interiors 203 and 204 across brine collection zone 237. Thus, feed fluid flows from interior 203 of vessel 102 to interior 204 of vessel 103 through transfer conduit 240 bypassing the volume 237 between bulkheads 238 and 239. Transfer conduit 240 is provided by hollow support strut 241 between bulkheads.

Transfer conduit could alternatively be used to convey feed fluid for the membrane strings of both half vessels through half vessel 102 to a feed manifold header in volume 237 between bulkheads 238 and 239, while the concentrate fluid from both half vessels would be returned to the concentrate discharge connection via the interstitial volume between the strings in half vessel 102. Both alternatives are encompassed in the statement that the feed entry connection and the concentrate discharge connection are provided on the closed head of one of the half vessels, with a transfer

conduit to convey fluid at substantially the working pressure axially past the membrane strings in that half vessel, the transfer conduit communicating from one of the feed entry connection or the concentrate exhaust connection to a bulkhead adjacent the vessel connector, so as to provide pressurized fluid connection between the free rotor booster pump assembly and the membrane strings in the other one of the half vessels.

Feed fluid enters the brine channel entrance 206 of first element 207 and the concentrate exits from last element 209 through brine channel exit 210 into brine connector 242 penetrating bulkhead 239. The brine connector 244 from a coaxially opposed membrane string in the opposite pressure vessel likewise penetrates bulkhead 238. Brine connectors 242 and 244 are extended to contact each other on face 245, so as to support the hydrostatic loads due to the pressure difference between the feed fluid in vessel interior 203 and 204, and the concentrate fluid in brine collection zone 237. Hence, the structural loads on bulkheads 238 and 239 are reduced.

Ports 246 are provided in brine connectors 242, so as to provide fluid communication from brine channel exit 210 to the brine collection zone 237.

Concentrate fluid is delivered from brine collection zone 237 by brine transfer conduit 250 penetrating bulkhead 238 and passing through interior 203 of vessel 102 to penetrate its head 231, and connect by conduit 131 to turbine 132. In the embodiment depicted, conduit 250 is installed coaxially to vessel 102 and annular channel 232, so that the central membrane string of vessel 102 must be eliminated. Alternatively, brine transfer conduit 250 or a plurality of similar conduits could be installed in the interstitial spaces between membrane support tubes 251 and vessel liner 107, so as to avoid loss of an entire membrane string.

Permeate fluid is withdrawn from typical product tube 119 through product tube connector 252 and delivery conduit 253 penetrating vessel head 254. The opposite end of product tube 119 is closed by plug 255.

Vessel 102 is mounted on fixed cradle 256, while vessel 103 may be moved by sliding on rails 170 for access to vessel interiors 102 and 103 when tie bolts 162 are disconnected. Cradle 168 may be moved back on rails 170 until vessel 103 clears connector sleeve 235, and then moved laterally sufficiently more than the maximum external diameter of the vessels and clamping collars, so as to allow unobstructed access into each of the vessel interiors. It then become possible to load fully assembled membrane strings into the support tubes, as an alternative to installing the membrane elements individually and assembling the membrane strings in situ.

Fully assembled membrane strings may be installed and removed using a mobile carriage with an elevating trough or barrel to ensure full support and alignment of the string being loaded into or removed from a support tube 118.

<u>Fig. 6</u>

Embodiment 270 shows a single vessel embodiment similar to embodiment 230. Vessel 103 and its membranes have been removed for a smaller scale application, using the same diameter vessel 102. Vessel 102 is closed by flanged head 271, having corrosion resistant liner 272, and retained by clamping collar 161. It will be evident that the feed and concentrate connections may be made to the closed head 231 of the vessel as shown, or to adjacent the open end 273 of the vessel as shown in Figs. 2 and 4. Likewise, the product may be delivered from either end of vessel 102.

Primary distinctions from the prior art are (1) the connection of both feed and concentrate conduits at one end

of the vessel, thus greatly reducing the length of external high alloy stainless steel or titanium piping, the use in some embodiments of the interstitial space between the membrane elements as a feed or concentrate flow conduit, and (3) installation and removal of the membrane elements from end of the pressure vessel so that the other end may be a closed head for much lower pressure vessel costs. Full diameter openings at both ends of the vessel would be prohibitively costly for large diameter pressure vessels, thus explaining why pressure vessels of larger inside diameter than the membrane element have not previously been commercially accepted.

Figs. 7, 8 and 9

Fig. 7 shows an integrated reverse osmosis module 300 according to the invention, with the pressure vessel and membrane elements oriented vertically. Fig. 8 shows a cross section view across the membrane element strings, defined by arrows 301 and 302 in Fig. 7. Fig. 9 shows a cross section view across the permeate and brine collection manifolds, defined by arrows 303 and 304 in Fig. 7. The elevation view of Fig. 7 is indicated by arrows 305 and 306 in Fig. 8, and 307 and 308 in Fig. 9.

Vertical pressure vessel 310 has a corrosion resistant liner 311. The vessel has a central cylindrical portion 312, an upper head 313 with an access hatch 314, and a lower head 315 with a plug 316. An important aspect of the invention here is that the diameters of the openings for hatch 314 and plug 316 are much smaller than the diameter of cylindrical portion 312, so as to reduce the pressure vessel cost by avoiding full diameter flanges. Vessel 310 is supported by pedestal ring 318.

A sealing flange 320 is provided in head 313 to receive hatch 314. Flange 320 is secured by retainer ring 321, with

static seal 322 to the vessel. Hatch 314 rests on seat 323 when the vessel is depressurized, and is retained against pressure loads by retainer ring 324. The hatch has a lift ring 325. Static seal 326 seals hatch 314 to flange 320.

A sealing flange 330 is provided in head 315 to receive plug 316. Flange 330 is secured by retainer ring 331, with static seal 332 to the vessel. Plug is located by seat 333 during assembly, and is retained against pressure loads by retainer ring 334. Static seal 336 seals plug 316 to flange 320.

Vessel 310 contains a honeycomb array of 55 membrane strings 340, shown in Fig. 8. Membrane string 340 has six membrane elements, including a first element 341, four intermediate elements 342 and a last element 343. In typical industrial practice, the elements will be 8" in diameter and 40" long. Hence, the active length of the membrane string would be 20', while the inside diameter of the vessel for 55 strings would be approximately 6'. Product tube 344 of the interconnected elements delivers low pressure permeate fluid through product connector 345. The opposite end of product tube 344 is closed by plug 346. Seal 347 is provided for product connector 345.

Pressurized feed fluid is delivered by booster pump 110 and feed entry connection 111 through penetration 350 in plug 316, to flood the internal space 351 of vessel 310 with feed fluid at the working pressure. The feed fluid flows through the interstitial volume 352 between the membrane strings to reach the upper space 353 of the vessel, and then enters the feed channel entrances 354 of all the first membrane elements 341 in parallel. Concentrate fluid leaves the brine channel exit 355 of the last membrane element 343 of typical string 340, flowing through brine connector 356 to a first brine manifold 357 defined by a horizontal vessel 358 within space 351.

The membranes deliver permeate fluid into product tube 344, discharging by product connector 345 with seal 347 into a first product manifold 360. As shown in Fig. 9, there are a total of nine first product manifolds, each collecting permeate fluid from a number of three to eight membrane strings from the total of fifty-five strings. Each first product manifold has a discharge branch 361 which is connected by seal 362 to a second product manifold 363. The single second product manifold 363 collects the product water from all nine first product manifolds, and delivers the total product flow through delivery branch 364. Delivery branch 364 coaxially penetrates plug 316 via seal 365, and discharges the product water through permeate delivery connection 366 which may be a bundle of separate conduits for each string or groups of strings.

As shown in Figs. 7 and 8, the first product manifold 360 is mounted concentrically within vessel 358. Consequently, first brine manifold 357 is provided by the annular space between first product manifold 360 and the inner wall of vessel 358. As shown in Fig. 9, there are a total of nine first brine manifolds, each collecting concentrate fluid from a number of three to eight membrane strings from the total of fifty-five strings, and each containing a first product manifold. Each first brine manifold has a discharge branch 370, connected by seal 371 to a second brine manifold 372, and containing a product discharge branch 361 mounted concentrically within. The single second brine manifold 372 is defined by horizontal vessel 373 within space 351, and is provided by the annular space between the inner wall of vessel 373 and the second product manifold 363 installed concentrically within vessel 373. The second brine manifold 372 collects the concentrate fluid from all nine first brine manifolds, and delivers the total concentrate flow through delivery branch 374. Delivery branch 374 coaxially penetrates plug 316 via seal 375 and passage 376, and discharges the concentrate fluid through concentrate discharge connection 131 to turbine 132.

In embodiment 300, the membrane strings 340 are preassembled before installation, either on site or by the membrane manufacturer before shipment. The preassembled membrane strings are installed in the vertical vessel 310 through the top opening when hatch 314 is opened or removed. The membrane strings 340 have a lifting point 380 for attachment to a special mobile crane, overhead gantry or installation tool. Each membrane string is guided into position in conically tapered ports for engagement of brine connector 356 and product connector 345 with their corresponding seals.

Membrane strings to be installed adjacent the vessel wall 311 are installed first, and must be swung laterally into position beneath head 313. Membrane strings near or on the vessel axis will be installed last. The membrane strings near the wall cannot be removed without first removing some of the membrane strings near the centre axis and directly below hatch 314. Once a membrane string 380 has been installed, it may be secured against tilting or bending by a lanyard 381 tying its lifting point 382 to an anchor point 383 in vessel head 313. No support tubes are needed.

The advantages of the vertical configuration include elimination of the internal membrane supports needed for the horizontal configuration, and the ability to use reduced diameter openings at <u>both</u> ends of the pressure vessels for lower vessel costs. Disadvantages include the need for specialized high clearance lifting equipment and skilled personnel for installing the fragile membrane strings in the vertical vessels. Installation and removal of membrane strings in the horizontal vessel embodiments is much simpler than in the vertical vessels.

It will be evident to those skilled in the art that all embodiments of the present invention provide simplified and more rapid installation and replacement of membranes, relative to the conventional method of manually inserting or

removing single elements in pressure vessels containing only a single string of elements. Each conventional vessel must be opened at both ends for membrane replacement, and considerable effort is required to push the complete string through the vessel since each element has a brine seal in frictional engagement with the inner wall of the vessel. Problems are often encountered with brine seals rolling over and twisting, or with spiral failure of critical product interconnector O rings.

In an important aspect of the present invention, brine seals are made between adjacent pairs of interconnected elements in a string, rather than between each element and the pressure vessel. After the membrane string has been assembled, preferably externally or at the membrane manufacturer's facility, no additional static sealing will be made on installing the string until the single brine seal of the brine connector and the static seal on the product connector are engaged.

Hence the membrane strings enter the vessel with negligible friction until the brine and product seals finally engage as the string is seated in position. Similarly, the strings are removed with negligible friction once the brine and product seals have been unseated. This invention allows use of the interstitial space between the membrane strings for feed or brine return flow, and further eliminates stagnant zones subject to bacterial or algal growth.

Fig. 10

Fig. 10 shows a membrane element string 400. For simplicity, string 400 is shown as having only three elements, although six to eight elements will often be used in larger scale installations.

Membrane string 400 has a first membrane element 401, an

intermediate element 402, and a last element 403. The elements are spiral wound elements, each having a product tube 410 around which is rolled one or a plurality of membrane leaves 411 into which product fluid permeates from the brine channels 412 established by a brine spacer mesh between adjacent leaves 411 and 413. Product tube interconnectors 415 with static seals 416 are provided to seal the product tubes between adjacent elements. End caps 420 and 421 are mounted on opposite ends of each membrane element (e.g. 402) to carry brine seals, and to restrain the membrane leaves against axial telescoping displacement under differential pressure loads due to the frictional pressure drop from feed to concentrate, as well as any transients during start-up and shutdown. The end caps have ports 422 for feed and concentrate flow entering and exiting the brine channel at opposite ends. Finally, a fiber glass wrap 423 is standardly applied to secure the complete assembly of end caps and the rolled membrane leaves against relative movement and against handling damage.

The description of the preceding paragraph applies to the conventional prior art construction and installation of spiral wound membrane elements. There, the brine seals are provided by a U cup seal installed in a groove in one of the end caps of each element. This U cup seal engages the inner wall of the prior art pressure vessel, whose inside diameter is slightly larger than the outside diameter of the membrane element. While preventing bypass of feed to that element, the brine seal in an end cap acts as a piston of the same diameter as the membrane housing, generating an axial compression force on the element and downstream elements in the string, proportionate to the brine channel pressure drop (typically about 5 psi) across that element. These compression forces must be supported by the already highly stressed product tube, and perhaps to some extent by the external wrap 423 and the end caps. As the cumulative compression force imposed on the last element is related to the length of the membrane string, the maximum practicable

length of the string (or the number of elements therein) has been constrained by this consideration.

In the present invention, brine seals are made from element to element, rather than between each element and an external tubular housing. Hence, the brine seals may be configured to have a significantly smaller diameter than the elements themselves, reducing the consequent axial compression loads within and between the elements. In embodiment 400, end cap 420 on element 402 has a female sealing surface engaging a male seal on end cap 424 on element 401, the brine seal being provided by O ring 425 on a diameter which may be much less than the element diameter.

The external sealing arrangement to be described will be suitable for embodiment 300. It will be evident that the brine and product connectors may be installed at the same end (as shown in Fig. 10) or at opposite ends of the string, and that the brine connector could be used for feed or brine connections equivalently, as appropriate for a given vessel configuration within the scope of the invention.

Feed water enters the brine channel entrance 430 of first element 401, while concentrate fluid is discharged from the brine channel exit 431 of last element 403 into brine connector 432. Sealing to the brine connector is provided by brine seal 433 on end cap 434 of element 403. Brine seal 435 will engage to the brine manifold of the pressure housing when the membrane string is installed and seated.

Permeate fluid from leaves 411 enters the low pressure internal space 440 of product tube through perforations in the product tube wall, and is delivered from last element 403 by product connector 441 sealed to last element product tube 442 by static seal 443. Product seal 444 will engage to the product delivery conduit or manifold of the pressure housing when the membrane string is installed and seated. A plug 445 is provided to close the product tube of the

first element 401.

Since the present invention envisages that the membrane strings will be installed and removed from one end of the pressure vessel, the other end being closed, it is necessary to provide a tensile connection between the elements in a string so that the string may be pulled to unseat the product and or brine seals, and then removed. This tensile connection may be provided as shown by straps 450 and 451, attached to opposite sides of the brine connector. The brine and product connectors may also be attached together to form a single assembly. Clamps 452 and 453 are provided respectively on straps 450 and 451, and will engage on flange 454 of end cap 455 on first element 401 (as indicated by arrow 456) to connect the entire string together. This arrangement of straps and clamps may be used either to instal and remove complete strings assembled externally, or else to instal and remove individual elements in horizontal vessel configurations. In the latter case, the straps are pulled to draw the string out for removal of each element in turn.

Alternatively, the elements of a string may be connected by mechanical clamps, latches or screw threads between the adjacent end caps of each adjacent pair of elements. In the case where the strings are assembled at the membrane supplier's factory, the elements may be bonded together end-to-end for positive attachment and sealing.

A further refinement within the invention is to use tapered brine channels to provide more uniform brine flow velocities within the string, and thus to avoid excessive pressure drops. Thus, the first element (receiving the full feed flow) would have the widest brine channel, while the last element (discharging the smaller concentrate flow) would have the narrowest brine channel. Such refinements will become practicable and desirable for very large installations as contemplated in the invention.

Fig. 11

Fig. 11 is a detail of an adjacent pair of end caps, showing an alternative brine seal arrangement for the membrane element string of Fig. 10. Sealing between a pair of adjacent end caps 424 and 420 is provided by a face seal 460 of elastomeric material. Flanges 461 and 462 on seal 460 ensure alignment, since the feed pressure outside the membrane string exceeds the pressure within the brine channel.

Fig. 12

Fig. 12 shows another alternative brine seal arrangement for the membrane element string of Fig. 10. End caps 424 and 420 respectively have circumferential grooves 470 and 471, as provided on prior art membrane elements for U cup brine seals. Brine seal 472 is provided as a collar (either split for assembly, or a stretchable elastomeric material). The sealing collar has flanges 473 and 474 which respectively engage grooves 470 and 471 for brine sealing and tensile connection between the elements of the string.

Fig. 13

Fig. 13 shows a pilot-operated shutoff valve 500 for detecting and isolating defective membrane element strings in the module of Fig. 7. Valve 500 is inserted between product connector 345 of each string 340 and corresponding first product manifold 360, and in fact provides the socket 501 for engaging and seating the product connector with seal 502 in manifold 360. The valve is axisymmetric about axis 503.

A small diameter plastic tube 505 is provided to extract samples of permeate fluid from the product connector of

string 340, and also as a hydraulic pilot line to close valve 500 should the permeate quality from string 340 become unacceptable even when blended with the product of the other strings.

Tube 505 and similar tubes for each of the other strings pass through the internal space 506 of the first product manifolds 360, and are bundled together to pass through the second product manifold 363, delivery branch 364 and product delivery conduit 366 and thus exit vessel 310 to an external area for extracting permeate samples and if necessary providing pilot actuation. Tube 505 only contacts product water at low pressure.

Tube 505 is connected by barbed fitting 510 to valve poppet 511. Poppet 511 contains a pilot piston 512, sealed by piston ring 513 within cylinder bore 514. Piston 512 acts against stops 515 in housing 516 of valve 500. Poppet 511 is also urged against stops 515 by compression spring 520, thus normally preventing engagement of poppet face 521 with seat 522 of housing 516. In the normally open position of the poppet, product flow moves downward from the membrane string and product connector 345, passes stops 515 and flow gaps 524 in poppet 511, past spring 520 and finally between face 521 and seat 522 to enter space 506 of first product manifold 360.

Whenever the plant operators wish to sample the permeate quality of string 340, the external end of tube 505 is opened to a pressure less than the low pressure in space 506. This pressure difference lifts annular disc 531 to allow flow of some permeate fluid through ports 530 to enter tube 505 as a sample to be tested for salinity. Annular disc 531 thus functions as a non-return valve for sample extraction. Equivalently, a spring loaded non-return valve in piston 512 could provide the same function.

If the product quality from string 340 becomes unacceptable,

either because of a severe membrane element failure or product tube static seal failure, the operator will connect the external end of the tube 505 to a source of fluid pressure (e.g. mains pressure) sufficiently greater than the low pressure in space 506 to drive piston 512 against stops 515, in turn overcoming spring 520 to close poppet face 521 against seat 522. As soon as the valve 500 closes, the pressure in the product tube of string 540 will build up to substantially feed pressure, thus closing valve 500 firmly until the module is shut down and depressurized. String 340 may thus be isolated (in terms of product delivery) until a conveniently scheduled module shutdown for membrane replacement or seal repair.

INDUSTRIAL APPLICABILITY

Application of the invention to large scale sea water desalination is demonstrated by the following figures and discussion. Component numerals in Figs. 14 to 16 follow the numerals of Fig. 1 for similar pumps and external conduits, and of Fig. 2 for module pressure vessels and vessel connectors.

<u>Fig. 14</u>

A 5 million gallon per day (5 MGD, or approximately 19,000 m^3/day) capacity of desalted water is provided by a single train (e.g. driven by a single high pressure prime mover). Three such 5 MGD trains would comprise a 15 MGD (approximately 57,000 m^3/day) plant. The train is driven by a single prime mover 11, driving pump 9; and has five modules 230 based on the configuration of Fig. 5. For Atlantic Ocean sea water desalination, estimated prime mover rating is 2750 kW. Each module has a free rotor booster pump 101 connected by very short high pressure feed and brine pipe runs to a stationary vessel 102, clamped to vessel 103 which is moved when the vessels are opened for

access to the membranes. Using the membrane array of fifty-five strings shown in Fig. 8 in vessel 103, and fifty-four strings in vessel 102 to allow for the brine return conduit, the module has 109 strings. Each string includes six thin film composite membrane elements of 8" (0.2 m) diameter and 40" (1.016 m) length, or four elements of 8" (0.2 m) diameter and 60" (1.524 m) length.

The 5 MGD capacity could also be provided as five 1 MGD trains, with one feed pump 9 for each module 230 as described above. However, economies of scale on both capital costs and efficiency of the larger feed pump will reduce life cycle product water costs by about 19 ¢/1000 gallons (5 ¢ / m^3) in this example, considering electrical power cost of 10 ¢/kWh in U.S. funds and a capital recovery factor of 18%.

The use of conventional prior art membrane housings strongly inhibits reverse osmosis train ratings much above 1 MGD (approximately 3800 m^3/day), owing to the high cost of manifolding and long pipe runs in a low packing density installation. The pressure vessels and modular configurations of the present invention provide a high packing density with much reduced costs of piping, enabling the use of much larger prime movers where appropriate, and also providing another cost saving for reduced capital charges of approximately 6 ¢/1000 gallons (1.6 ¢ / m^3) of product water.

<u>Fig. 15</u>

Fig. 15 shows a 50 million gallon per day (approximately 189,000 m^3/day) reverse osmosis sea water desalination train. Here, the same pressure vessel configuration and capacities are used as in Fig. 14, but the modules are now doubled with twinning of the pressure vessels coupled to a single free rotor booster pump. The free rotor booster pump assembly

101 is here connected to the end of a pressure vessel assembly including half vessels 102 and 103 with vessel connector 104 and delivering permeate to conduit 30, and in parallel with similarly short pipe runs to a second pressure vessel assembly including half vessels 102′ and 103′ with vessel connector 104′ and delivering permeate to conduit 30′. In these modules of 5 MGD rating, the large free rotor booster pump will enjoy significantly higher efficiency, while further reducing capital cost per unit of product capacity rating. The 50 MGD train could be powered by a single gas turbine of 23,300 kW rating, and might be part of a plant of say 250 MGD with five such trains.

A further striking application of the invention may be provided in the Dead Sea solar hydroelectric project. There, diversion of upstream waters for irrigation has resulted in evaporation shrinkage of the Dead Sea, which is approximately 400 m below sea level. It has been proposed to drive a tunnel under Israel and Palestine from the Mediterranean Sea, and then generate an average hydroelectric power of approximately 300 megawatts by supplying sea water to the Dead Sea through hydroelectric turbines. Alternatively and currently favoured by the Israeli government, Red Sea water could be pumped up a canal along the rift valley on the Jordanian border, and then released into the Dead Sea to generate hydroelectric power. It has been proposed to build the tunnel and/or canals and hydroelectric generators with a larger capacity rating of say 800 megawatts, so that the plant could be run intermittently to generate peaking power. Most recently, the preferred concept has been to use the hydroelectric power to operate an extremely large sea water reverse osmosis plant, whose concentrate water would be discharged to the Dead Sea.

In the present invention using 5 MGD modules as shown in Fig. 15, or even larger modules based on larger free rotor booster pumps, pretreatment plant 6 might be located on the

Mediterranean shore. If the high pressure modules are located approximately 400 m below sea level adjacent the Dead Sea, conduit 20 may represent a tunnel under Israel and Palestine, including penstocks to deliver the gravitationally pressurized sea water to manifold 20 and the free rotor booster pumps 101 in parallel. Pump 9 and prime mover 11 may now be eliminated, since the 400 m head (at Dead Sea elevation below sea level) of the sea water supplied to manifold 20 is enough for the reverse osmosis plant to operate at a pressure equivalent to a head of about 700 m and at 35% recovery, thanks to the pressure boost from the free rotor booster pumps discharging brine to the Dead Sea at substantially atmospheric pressure.

Based on continuous and steady flow, a single lined tunnel of 6 m diameter (or a pair of 4 m tunnels) could convey the sufficient flow to make up the solar evaporation deficit of the Dead Sea. This flow is sufficient, either to generate some 300 megawatts of electrical power continuously, or to produce approximately 400 MGD of fresh water at the Dead Sea shore using 8 trains and 80 modules as indicated in Fig. 15 (minus the high pressure pumps), or to produce some combination of electric power and desalted water. Separate product water pumping, conveyance and storage facilities would be required to deliver the product water at higher elevations to users in Israel, Palestine and Jordan. The product water lift pumps could be oversized and operated discontinuously in order to make most economic use of off-peak power, as well as solar energy, while the reverse osmosis plant would most economically run continuously at essentially full capacity.

Fig. 16

Fig. 16 shows a 75 million gallon per day (approximately 284,000 m^3/day) reverse osmosis sea water desalination plant with five 15 MGD (approximately 284,000 m^3/day) trains, each

powered by a 7,500 kW gas turbine. Such large plants may be required imminently in several locations including Florida, California and Singapore. The prior art would typically use 1 MGD trains powered by 600 kW electric motors, while the present invention enables modularization and economies of scale to reduce capital costs of pressure vessels, pipework and pumps. Important operating cost savings may be provided through direct powering by natural gas fuelled combustion turbines. The estimated reduction in desalted water costs, compared to prior art reverse osmosis using the same membranes, is approximately 53 ¢ /1000 gallons (14 ¢ /m^3), based on electrical power cost of 6 ¢ / kWh, natural gas cost of \$2 /GJ, and a capital recovery factor of 12 %.

Important efficiencies of scale are projected for electrical power consumption for sea water reverse osmosis desalination trains as the train capacity is expanded in the range from 1 to 100 million gallons per day. For an Atlantic Ocean application, specific power consumption would drop from 4.7 kWh/m^3 at 1 MGD train capacity to 3.8 kWh/m^3 at 50 MGD train capacity. The modularization strategy of the present invention thus achieves a significant impact on energy efficiency.

It will be seen that separate levels of the invention apply to improved modular configurations at the three main levels of (1) the membrane strings, (2) the pressure vessels and high pressure pipework, and (3) hydraulic machinery and prime movers for feed pumping and concentrate energy recovery. While the above three levels have been described in combination within integrated embodiments to achieve the highest combined benefits, each level of the invention may also be exploited separately. Thus, the improved brine seals disclosed herein for membrane strings may be used in conventional reverse osmosis pressure housings, for simplified assembly and other advantages. The inventive pressure vessels disclosed herein for multiple membrane strings may be used in conjunction with free rotor booster

pumps, or may be used instead or with alternative fluid machinery including the use of a single energy recovery turbine on a common shaft with each high pressure feed pump and its prime mover. Also, multiple modules defined by free rotor booster pumps may be supplied in parallel by a single feed pump, without necessarily using the integrated pressure vessels containing multiple membrane strings.

However, the three main levels of the invention do combine powerfully for multiplied benefits. The improved brine seals enable easy installation and removal of the membrane strings from one end of the pressure vessels, thus allowing the other end to have a substantially closed head (e.g. much smaller than full diameter opening) for greatly reduced vessel costs. The improved brine seals also facilitate use of the interstitial voids between membrane strings to transfer feed or concentrate fluid internally from one end to the other end of the vessel, thus allowing all high pressure connections to be made at one end of the vessel. This in turn facilitates connection one or two or possibly more pressure vessels to a single free rotor booster pump with the shortest possible high pressure pipe connections. In turn, the compactness of the modules, with dense packing of the membrane strings in the pressure vessels compared to the low density packing of membranes in arrays of prior art pressure vessels mounted on racks, again enables the connection of multiple modules in parallel to a single feed pump with relatively short pipe runs. Here, a special advantages of the free rotor booster pump is that the connection to the feed pump is at a medium pressure, substantially less than the full membrane working pressure. Hence, the very high cost of high alloy pipework can be greatly reduced, while the high pressure portion of the reverse osmosis plant has a very small footprint. All of the above benefits enable very large reverse osmosis plants to be modularized with trains having large feed pumps and prime mover, one or even two orders of magnitude larger than the feed pumps of conventional reverse osmosis trains. This

allows further important economies of scale in capital cost reduction, high energy efficiency, and opportunities to use combustion turbines or steam turbines as direct prime movers so that energy costs may be as low as possible for large scale desalination.

CLAIMS

1. Apparatus for reverse osmosis separation of a feed fluid into permeate and concentrate fluid fractions by contacting the feed fluid at a working pressure with selective membrane means permeating the permeate fluid and rejecting the concentrate fluid, with a permeate recovery ratio defined by the ratio of permeate flow to feed flow, the feed fluid containing a solute to be substantially removed from the permeate fluid and concentrated into the concentrate fluid, the apparatus including a number of modules with each module having:

   (a) a number of membrane elements in which the membrane means concentrate the solute in the feed fluid admitted to the membrane elements at substantially the working pressure, while delivering permeate fluid at low pressure,

   (b) a number of pressure vessels containing the membrane elements, with each vessel having a feed entry connection, a concentrate discharge connection, and a permeate delivery connection, and with the membrane elements installed as a plurality of membrane strings in each vessel, each membrane string comprising a number "L" of membrane elements disposed axially and in which the feed fluid is concentrated successively to the concentration of the concentrate fluid, so that the string includes a first element to which the feed fluid is admitted and a final element from which the concentrate fluid is delivered,

   (c) brine sealing means to direct feed fluid from the feed port to the first membrane element in each string, then to direct successively concentrated feed fluid between the "L" membrane elements in series within the string, and then directing

concentrate fluid from the final membrane element of each string to the concentrate discharge connection,

(d) a permeate manifold to collect the permeate fluid from the membrane strings in parallel and to deliver the permeate from the pressure vessel,

(e) a booster pump assembly comprising a booster pump and a turbine coupled to the booster pump, the booster pump receiving feed fluid at a feed supply pressure less than the working pressure and delivering the feed fluid to the feed entry connection of the pressure vessel at substantially the working pressure, the turbine receiving concentrate fluid from the concentrate discharge connection of the pressure vessel and expanding the concentrate fluid from substantially the working pressure to an exhaust pressure so as to power the booster pump,

and the apparatus also having feed fluid supply means delivering feed fluid to the booster pump at the feed supply pressure.

2. The apparatus of claim 1, in which the feed supply pressure is greater than the working pressure multiplied by the permeate recovery ratio, and further characterized by the booster pump assembly being a free rotor booster pump assembly with the turbine being the sole source of mechanical power to drive the booster pump.

3. The apparatus of claim 2, with a plural number of said modules fed from a single feed fluid supply means, and the feed fluid supply means including a feed supply manifold to deliver feed fluid at the feed supply pressure to the modules in parallel.

4. The apparatus of claim 3, in which the feed supply means further includes a feed pump pressuring the feed fluid to the feed supply pressure, the feed pump being driven by a prime mover.

5. The apparatus of claim 4, with the prime mover being an electric motor.

6. The apparatus of claim 5, with the electric motor having variable frequency speed control so as to regulate the feed pump.

7. The apparatus of claim 4, with the prime mover being an gas turbine.

8. The apparatus of claim 4, with the prime mover being an steam turbine.

9. The apparatus of claim 3, with the feed supply pressure substantially established by a gravitational head.

10. The apparatus of claim 2, in which the pressure vessel contains a number "M" of membrane strings within a substantially cylindrical and horizontally aligned portion of said vessel.

11. The apparatus of claim 10, in which M = 1.

12. The apparatus of claim 10, in which M > 1, and the membrane strings are installed in support tubes aligned in parallel with the vessel and forming a hexagonally packed bundle in the vessel.

13. The apparatus of claim 10, in which the module has a single pressure vessel, and all membrane strings in the vessel have the same number of elements, so that the total number of membrane elements in the module is "N" with N = M X L.

14. The apparatus of claim 10, with a transfer conduit to convey fluid at substantially the working pressure axially past the membrane strings in the vessel.

15. The apparatus of claim 10, in which the module has two pressure vessels each with feed entry and concentrate discharge connections to the free rotor booster pump assembly.

16. The apparatus of claim 10, in which the pressure vessel is provided as two half pressure vessels joined by a full diameter vessel connector, each half vessel having a cylindrical portion having an internal diameter, each half vessel further having a closed head at a first end of the cylindrical portion and a full diameter opening with a fluid seal to the vessel connector at a second end of the cylindrical portion, and each half pressure vessel containing a bundle of membrane strings.

17. The apparatus of claim 16, in which an external flange is provided at the second end of the half vessel, and the half vessel is clamped by the flange to the vessel connector.

18. The apparatus of claim 16, with the feed entry connection and the concentrate discharge connection provided on the vessel connector.

19. The apparatus of claim 18, with the permeate delivery connection also provided on the vessel connector.

20. The apparatus of claim 16, with the permeate delivery connection provided on the closed heads of the half vessels.

21. The apparatus of claim 16, with the feed entry connection and the concentrate discharge connection provided on the closed head of one of the half vessels,

and with a transfer conduit to convey fluid at substantially the working pressure axially past the membrane strings in that half vessel, the transfer conduit communicating from one of the feed entry connection or the concentrate exhaust connection to a bulkhead adjacent the vessel connector, so as to provide pressurized fluid connection between the free rotor booster pump assembly and the membrane strings in the other one of the half vessels.

22. The apparatus of claim 16, with means to move one of the half pressure vessels from the vessel connector to provide access for servicing and membrane replacement.

23. The apparatus of claim 16, with means to move both of the half pressure vessels from the fixed vessel connector so as to provide access for servicing and replacement of the membrane strings in that half vessel.

24. The apparatus of claim 2, in which the pressure vessel contains a number "M" of membrane strings installed abreast and vertically in hexagonal array within a substantially cylindrical and vertically aligned portion of said vessel.

25. The apparatus of claim 24, with an access hatch of diameter less than the diameter of the cylindrical portion of the vessel, the access hatch being provided at the top of the vessel for installing and replacing the membrane strings.

26. The apparatus of claim 24, with manifolds within the vessel for collecting permeate and concentrate fluid from the membrane strings, said manifolds communicating respectively to permeate delivery and concentrate discharge connections in a plug at the lower end of the

vessel, said plug also including the feed entry connection admitting feed fluid at the working pressure to the interior of the vessel.

27. The apparatus of claim 1, further including permeate test means to detect solute concentration in the permeate fluid from membrane elements.

28. The apparatus of claim 27, further including means to stop permeate flow from defective membrane strings, without shutting down operation of the module.

29. The apparatus of claim 27, in which the permeate test means includes a sample valve cooperating with the permeate collection manifold for withdrawing samples of permeate from membrane elements.

30. Apparatus for reverse osmosis separation of a feed fluid into permeate and concentrate fluid fractions by contacting the feed fluid at a working pressure with selective membrane means permeating the permeate fluid and rejecting the concentrate fluid, the feed fluid containing a solute to be substantially removed from the permeate fluid and concentrated into the concentrate fluid, the apparatus including at least one module with the module comprising:

(a) a number "N" of spiral wrap membrane elements in which the membrane means concentrate the solute in the feed fluid admitted to the membrane elements at substantially the working pressure, while delivering permeate fluid at low pressure;

(b) a pressure vessel containing the membrane elements, the vessel having a vessel axis defining first and second ends of said vessel, with the vessel having a substantially cylindrical portion coaxial to the vessel axis; the vessel having a

feed entry connection to provide feed fluid to the module, a concentrate discharge connection to deliver concentrate fluid from the module, and a permeate delivery connection to deliver permeate fluid from the module;

(c) a number "M" of at least one membrane strings within the vessel, each such string comprising a plurality of membrane elements disposed in line parallel to the vessel axis, the membrane elements of each string including a first membrane element and a last membrane element, the string having a feed end to which feed fluid is admitted to the first membrane element of the string and a concentrate end from which concentrate fluid is discharged from the last membrane element of the string, so that feed fluid is concentrated successively in the membrane elements along the string from the feed end to the concentrate end,

(d) brine seal means between each adjacent pair of membrane elements in a membrane string so as to define a brine flow channel in which the feed fluid is successively concentrated through the membrane elements of the string while contacting the membranes therein, the brine channel extending from the feed end to the concentrate end of the string; with the brine seal means sealing directly between adjacent pairs of elements in the membrane string, so as to prevent fluid communication between the pressure vessel and the brine channel intermediate between the first and last membrane elements of the string;

(e) permeate product delivery means to collect the permeate fluid from the membrane elements in each string, including product tube interconnector sealing means between each adjacent pair of

membrane elements in a membrane string, and conduit means to deliver the permeate fluid to the permeate delivery connection.

31. The apparatus of claim 30, further including a tensile connection between the membrane elements in a membrane string.

32. The apparatus of claim 30, with a plural number of membrane strings in a hexagonally packed bundle within the vessel.

33. The apparatus of claim 30 with brine sealing means between the pressure vessel and the concentrate end of the last element in each membrane string, so that the brine channel communicates to the concentrate discharge connection, while the feed entry connection communicates to the interior of the pressure vessel so that the pressure vessel void volume external to the membrane elements is flooded with feed fluid at the working pressure and communicates to the feed end of the first membrane element of each membrane string.

34. The apparatus of claim 30 with brine sealing means between the pressure vessel and the feed end of the first element in each membrane string, so that the brine channel communicates to the feed entry connection, while the concentrate discharge connection communicates to the interior of the pressure vessel so that the pressure vessel void volume external to the membrane elements is flooded with concentrate fluid at the working pressure and communicates to the concentrate end of the last membrane element of each membrane string.

35. The apparatus of claim 30, with the module also including a booster pump assembly comprising a booster pump and a turbine coupled to the booster pump, the

booster pump receiving feed fluid at a feed supply pressure less than the working pressure and delivering the feed fluid to the feed entry connection of the pressure vessel at substantially the working pressure, and the turbine receiving concentrate fluid from the concentrate discharge connection of the pressure vessel and expanding the concentrate fluid from substantially the working pressure to an exhaust pressure.

36. The apparatus of claim 34, in which the feed supply pressure is greater than the working pressure multiplied by the permeate recovery ratio, and further characterized by the booster pump assembly being a free rotor booster pump assembly with the turbine being the sole source of mechanical power to drive the booster pump.

37. Process for reverse osmosis separation of a feed fluid into permeate and concentrate fluid fractions by contacting the feed fluid at a working pressure with selective membrane means permeating the permeate fluid at low pressure and rejecting the concentrate fluid at substantially the working pressure, with a permeate recovery ratio defined by the ratio of permeate flow to feed flow, the feed fluid containing a solute to be substantially removed from the permeate fluid and concentrated into the concentrate fluid, the process including:

(a) pressurizing the feed fluid to a feed supply pressure, the feed supply pressure being less than the working pressure but greater than the working pressure multiplied by the permeate recovery ratio,

(b) delivering the feed fluid in parallel to a plurality of modules connected in parallel to the feed supply manifold, each of said modules

including a free rotor booster pump assembly and a number "N" of membrane elements within a pressure vessel,

(c) within the free rotor booster pump assembly of each module, boosting the pressure of the feed fluid from the feed supply pressure and delivering the feed fluid to the membrane elements of the module at substantially the working pressure, while expanding the concentrate fluid to an exhaust pressure so as to power the free rotor booster pump assembly, and

(d) delivering the permeate fluid from the modules.

38. The process of claim 37, further characterized by operating a prime mover to drive a feed pump to pressurize the feed fluid to the feed supply pressure.

39. The process of claim 37, further characterized by pressurizing the feed fluid to substantially the feed supply pressure by the gravitational head of installing the module at an elevation below sea level, while releasing the concentrate fluid at that elevation after expanding the concentrate fluid through the free rotor booster pump assembly to substantially atmospheric pressure.

40. The process of claim 39, further conducted at a location adjacent the Dead Sea for desalination of Mediterranean Sea water, and conveying the Mediterranean Sea water by tunnel to the Dead Sea basin.

41. The process of claim 37, further characterized by installing the membrane elements in horizontal support tubes in a hexagonally packed bundle within a pressure vessel of a module.

42. The process of claim 41, further characterized by moving a portion of the pressure vessel in the horizontal place, so as to gain access for servicing and membrane replacement.

43. The process of claim 36, further characterized by installing preassembled membrane strings vertically through the top of a pressure vessel of a module.

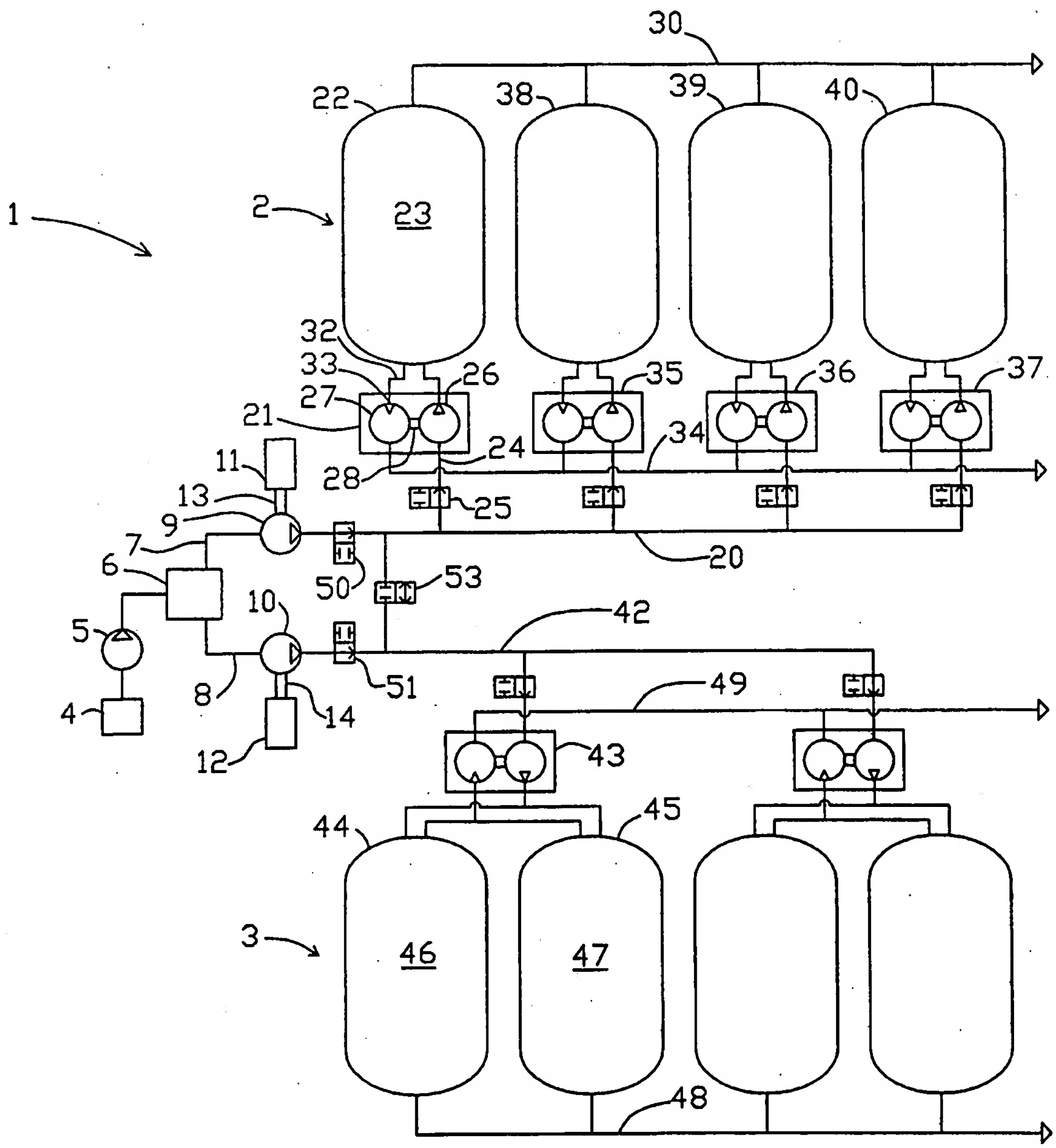

30
22
38
39
40
23
1
2
32
33
26
35
36
37
27
21
24
34
11
28
13
25
9
7
20
6
50
53
10
42
5
49
51
4
8
14
43
12
44
45
3
46
47
48

Fig. 1

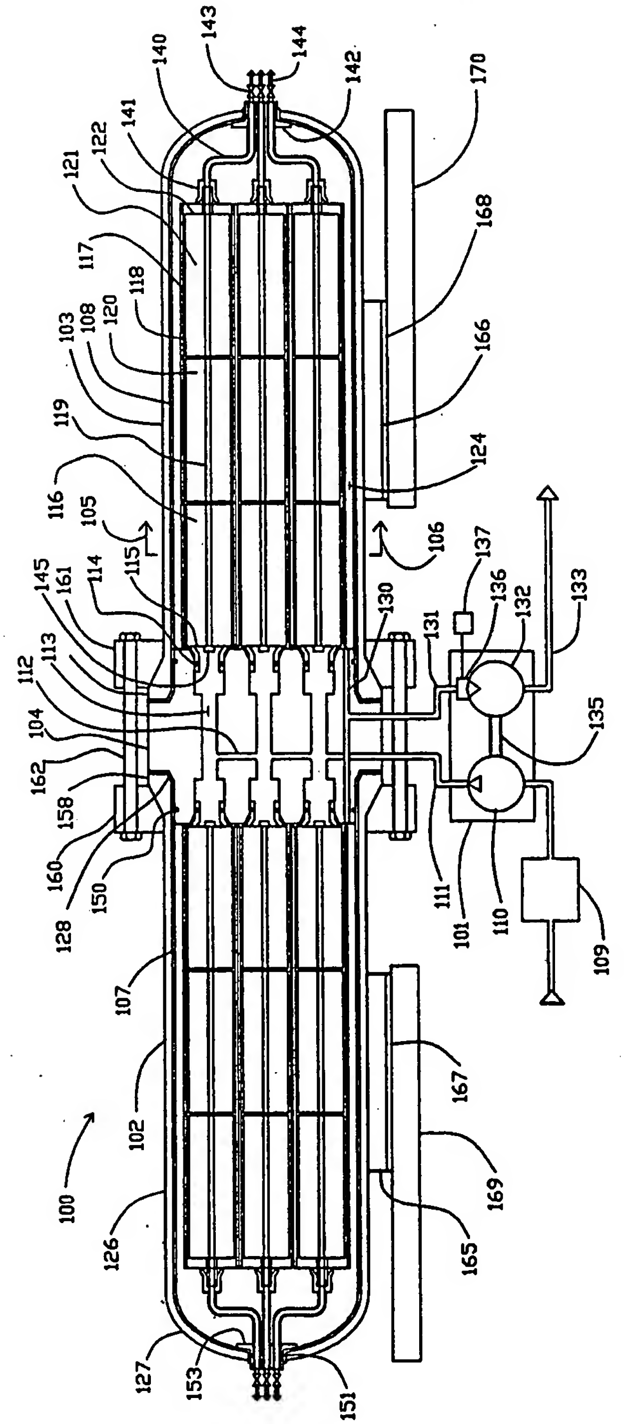

143
144
140
142
170
121
122
141
117
118
120
103
108
168
166
119
124
116
105
106
137
145
161
114
115
130
131
136
132
133
112
113
135
104
162
158
160
150
128
111
101
110
109
107
102
167
100
169
126
165
127
153
151

Fig. 2

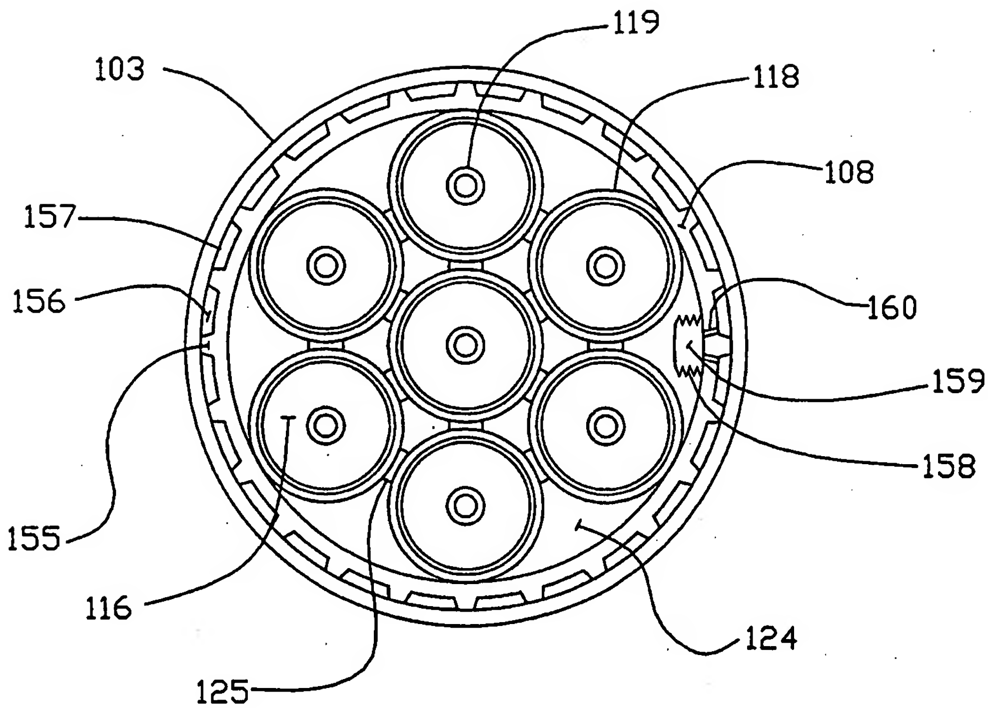


Fig. 3

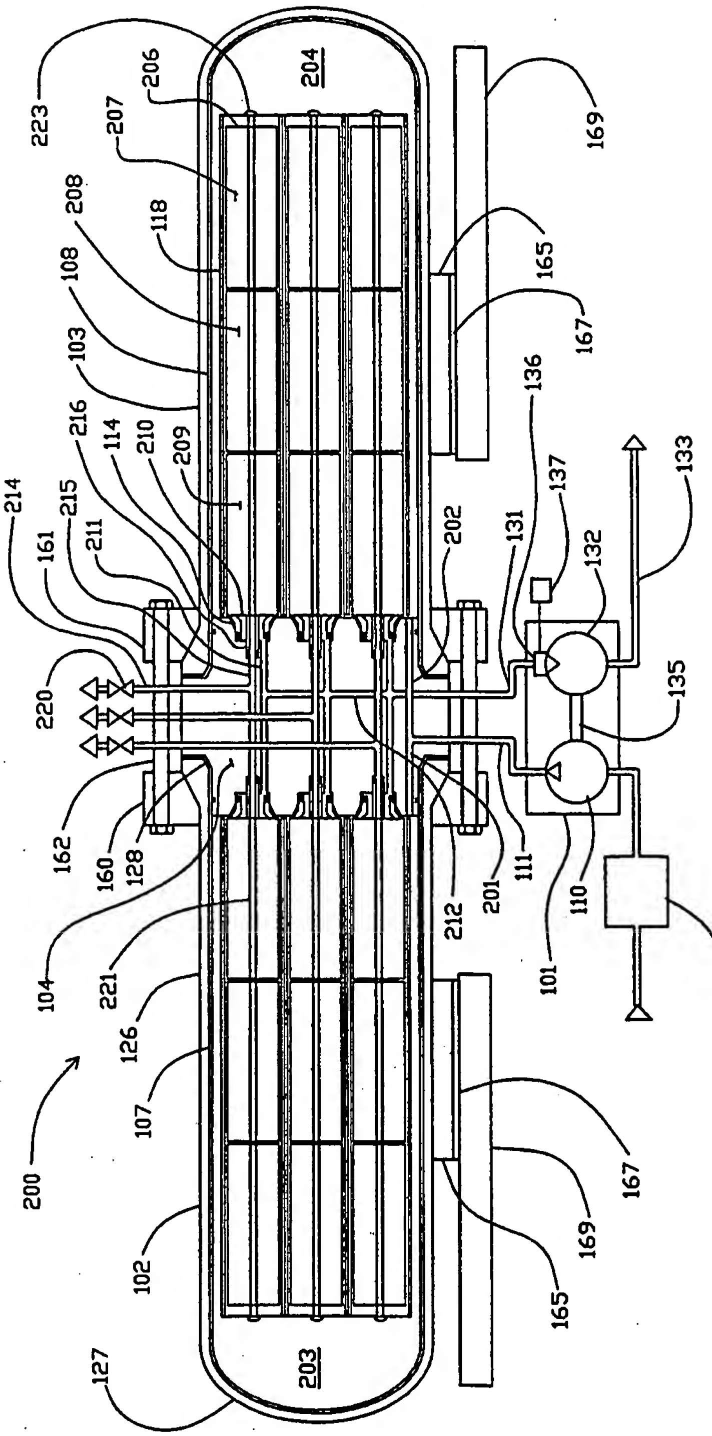
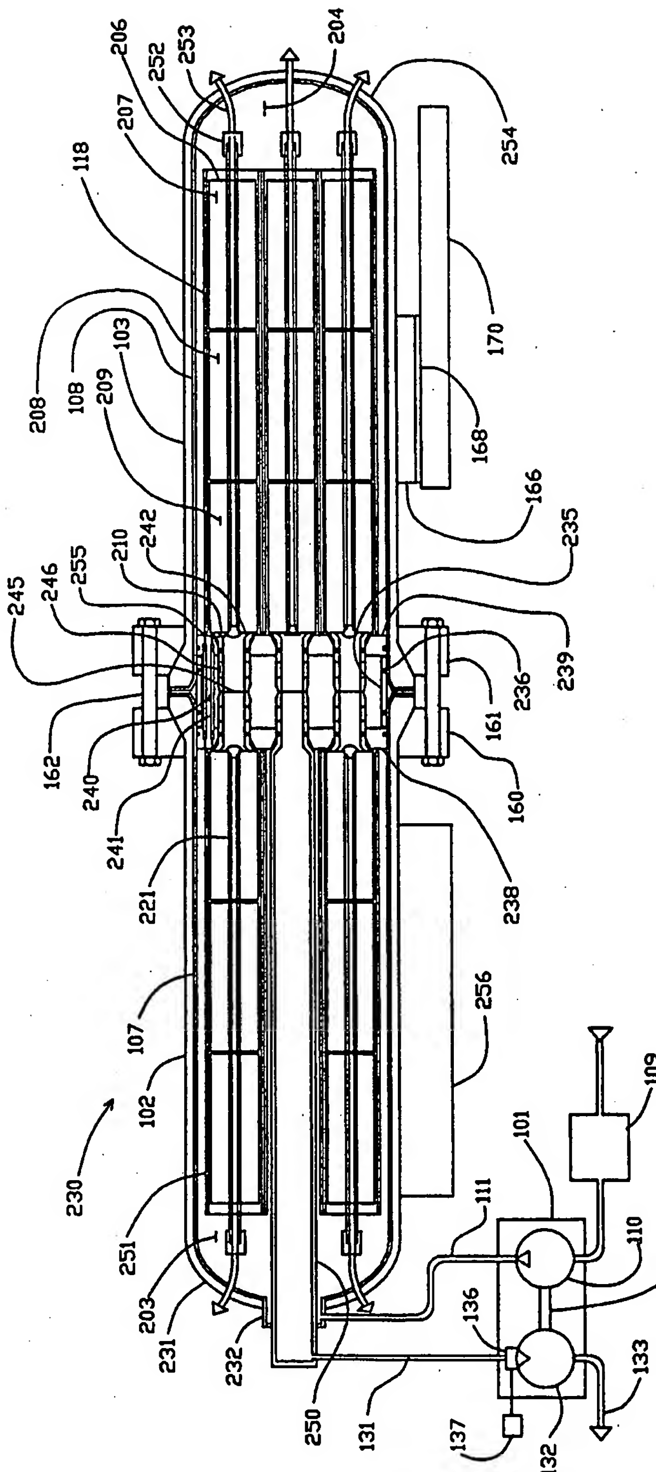

204
203
200
223
206
207
208
118
108
103
216
114
210
209
214
215
211
161
220
162
160
128
104
221
126
107
102
127
169
165
167
136
137
133
202
131
132
135
212
201
111
110
101
109

Fig. 4



206
252
253
204
254
207
118
170
208
108
103
209
168
166
235
210
242
255
246
245
239
236
161
162
240
160
241
238
221
256
107
109
102
230
101
111
251
110
135
203
231
136
232
133
250
131
137
132

Fig. 5

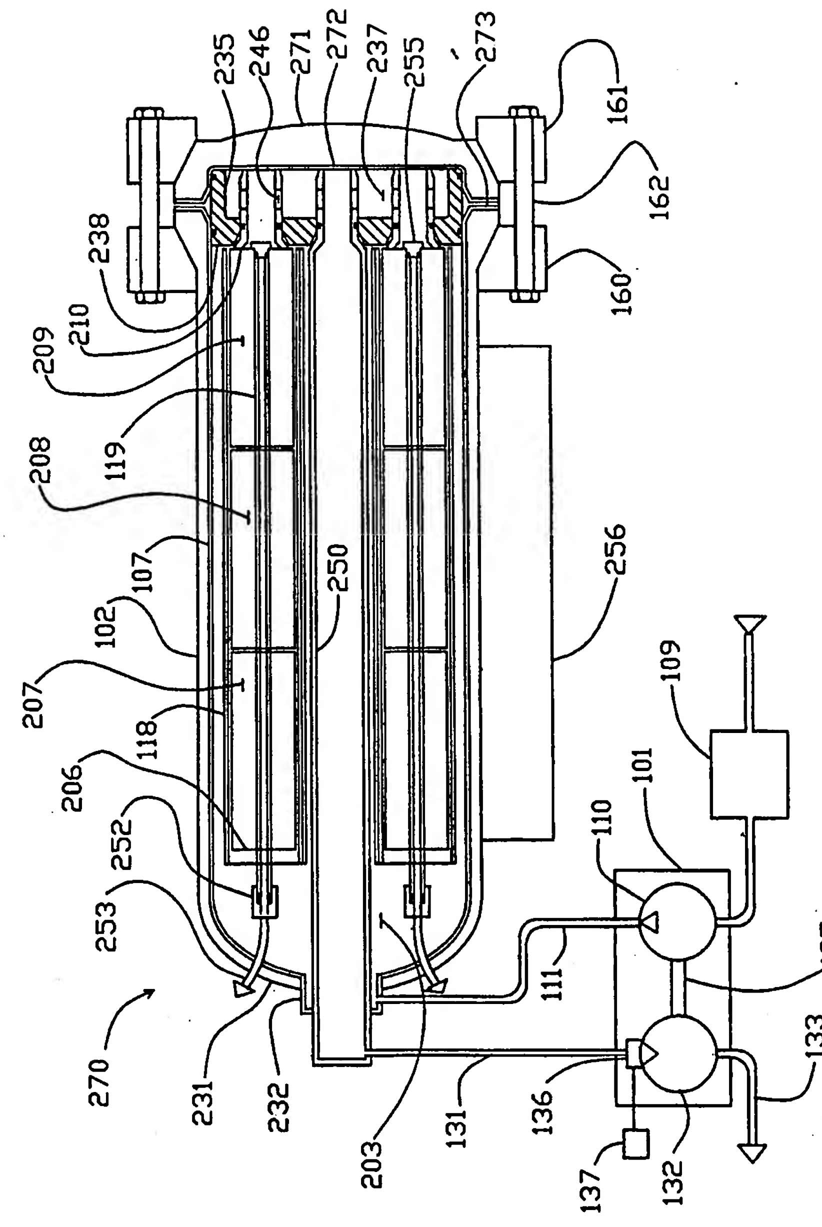

235
246
271
272
237
255
273
161
162
160
238
210
209
119
208
107
102
250
256
207
118
206
252
253
109
101
110
135
111
133
270
231
232
203
131
136
132
137

Fig. 6

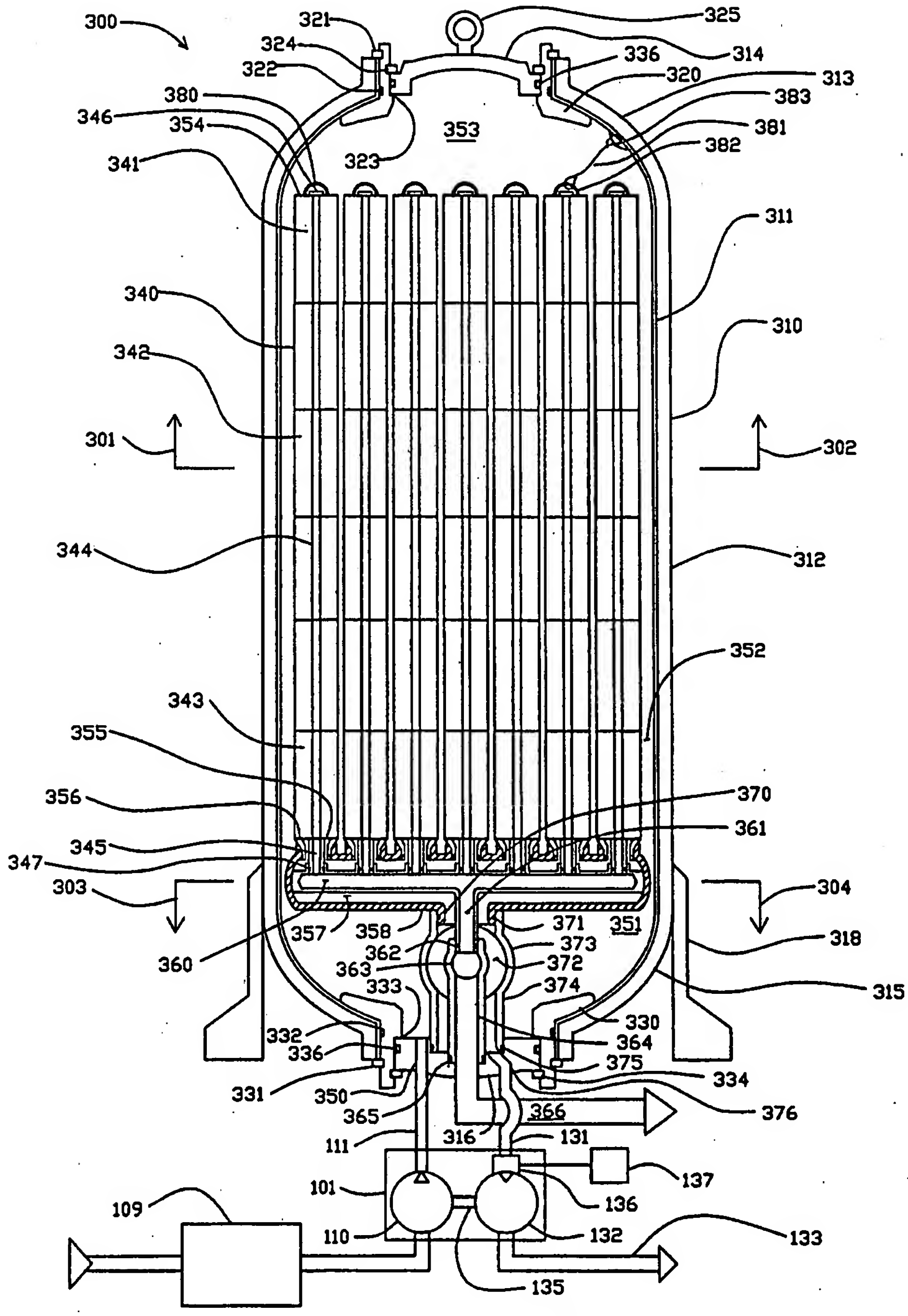

300
321
324
322
380
346
354
341
323
353
325
336
314
320
313
383
381
382
311
340
342
310
301
302
344
312
352
343
355
356
345
347
303
370
361
304
360
357
358
371
351
318
362
373
363
372
374
333
315
332
336
330
364
375
334
331
350
365
366
376
111
316
131
137
101
136
109
110
132
133
135

Fig. 7

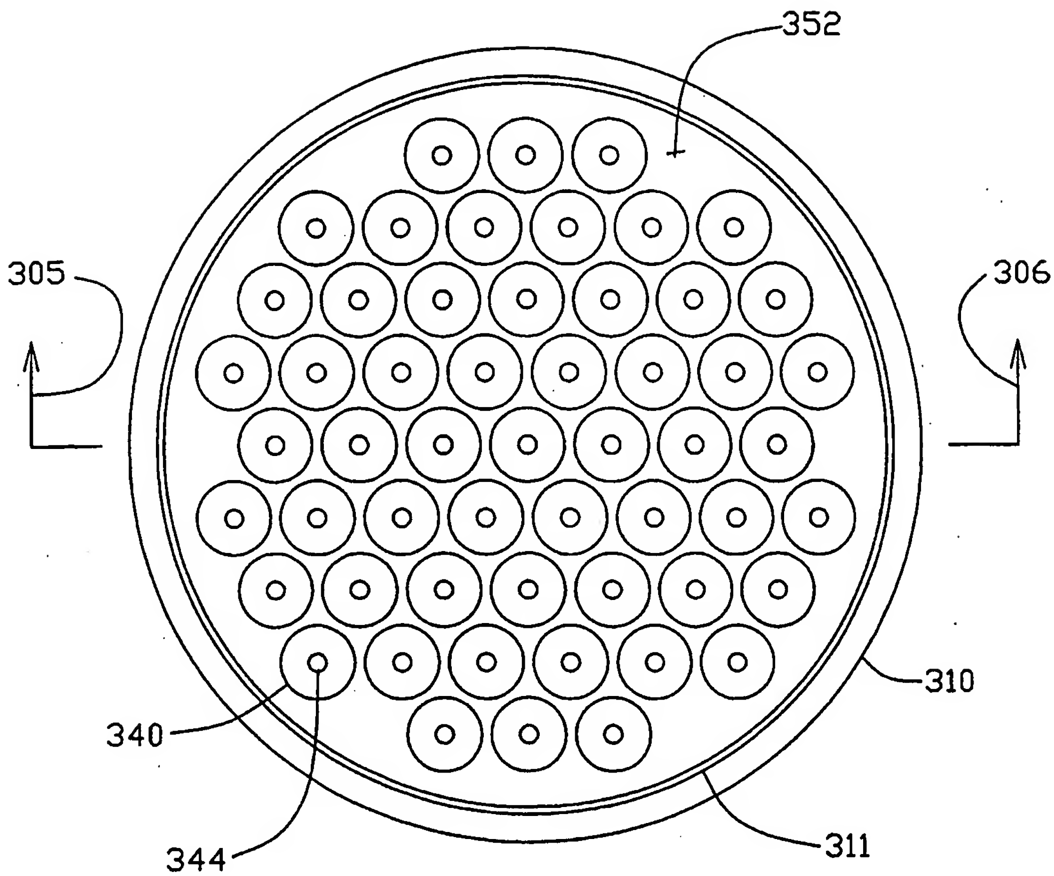


Fig. 8

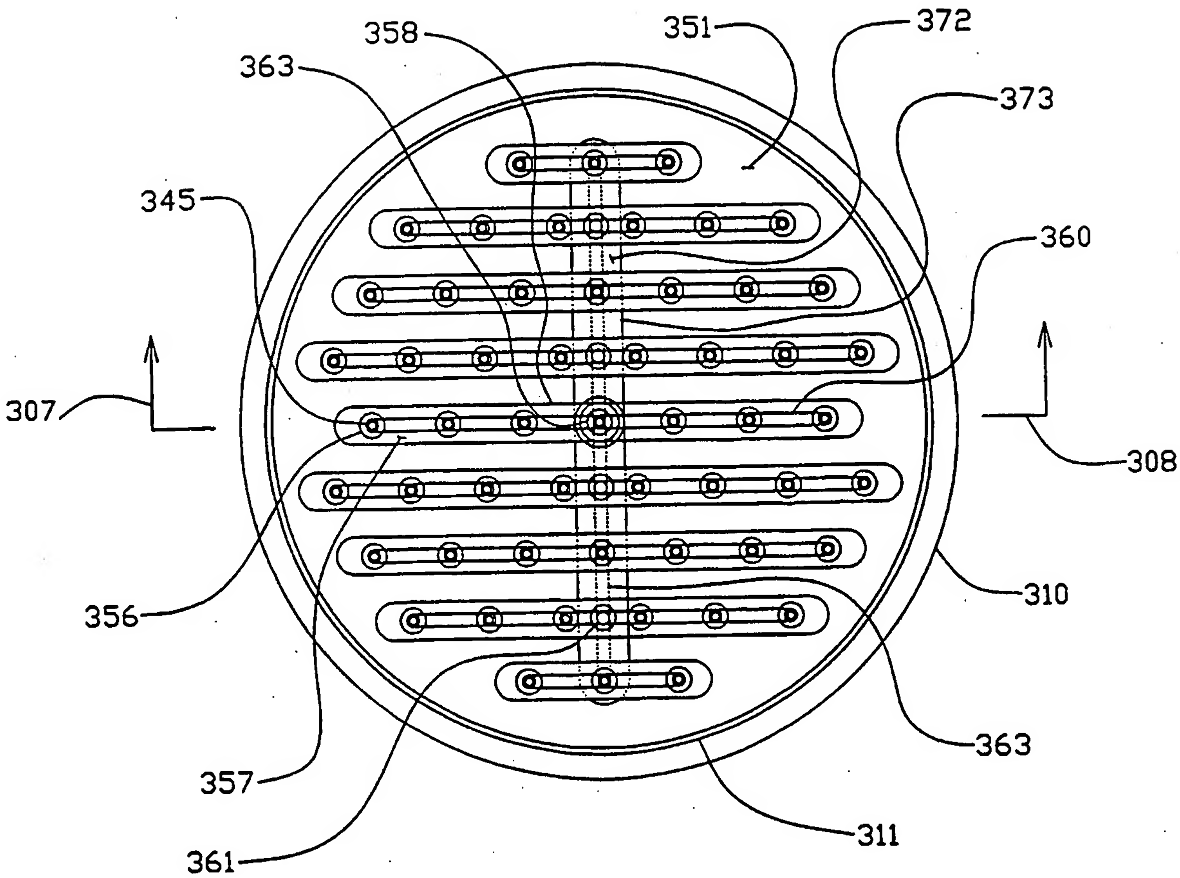
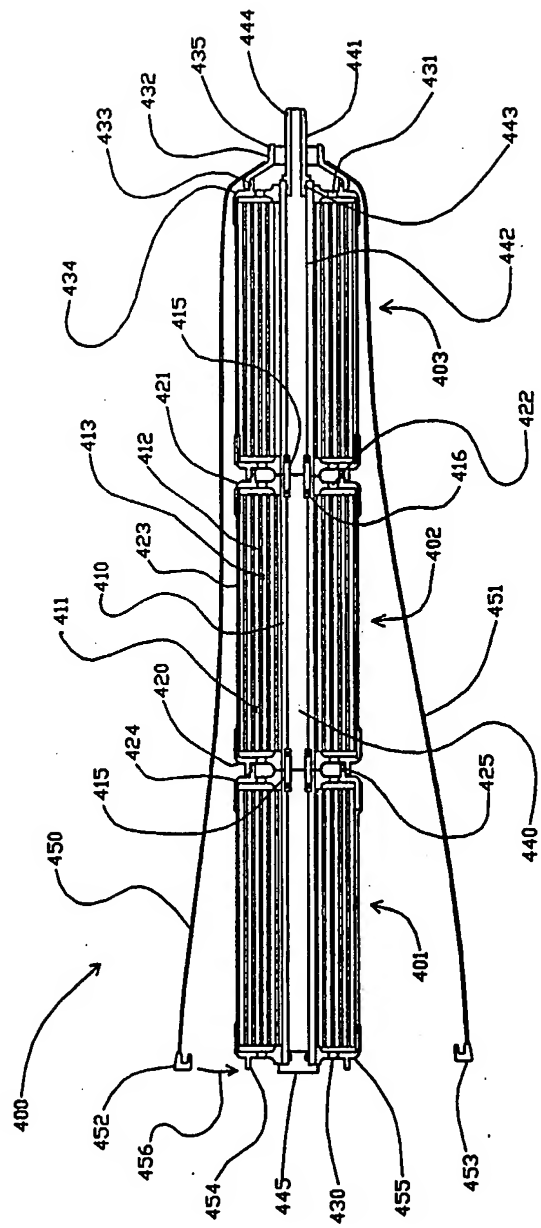


Fig. 9



400
401
402
403
410
411
412
413
415
416
420
421
422
423
424
425
430
431
432
433
434
435
440
441
442
443
444
445
450
451
452
453
454
455
456

Fig. 10

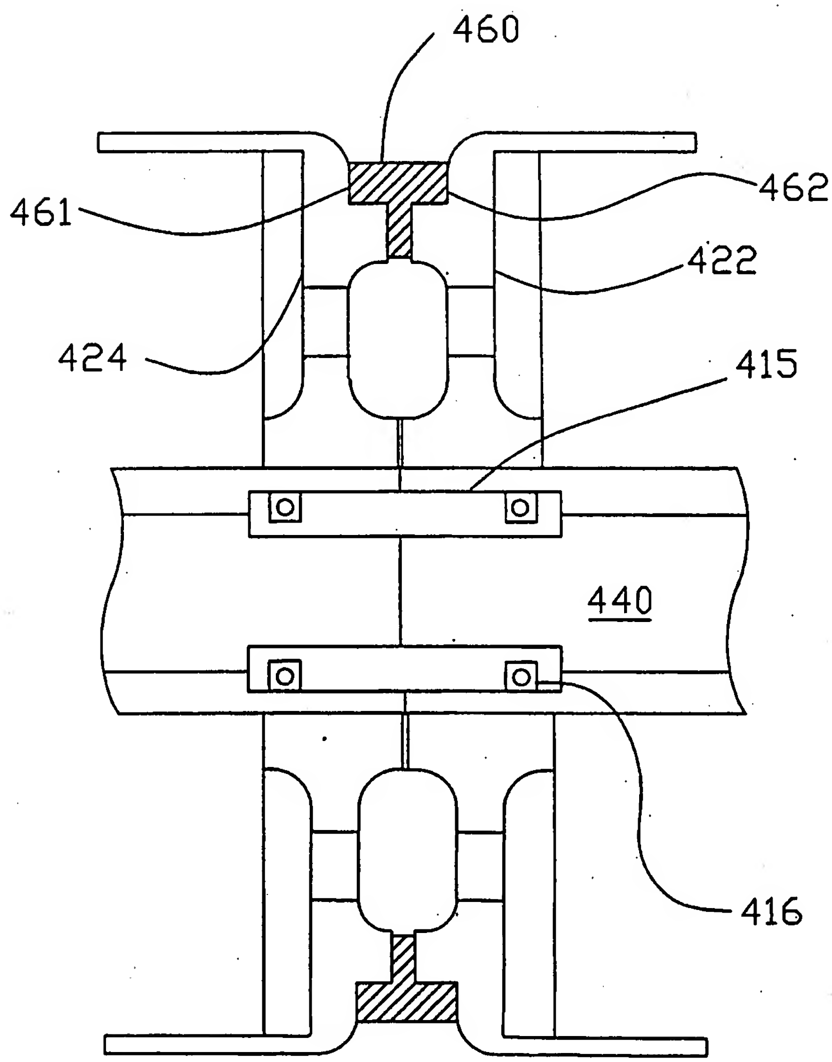


Fig. 11

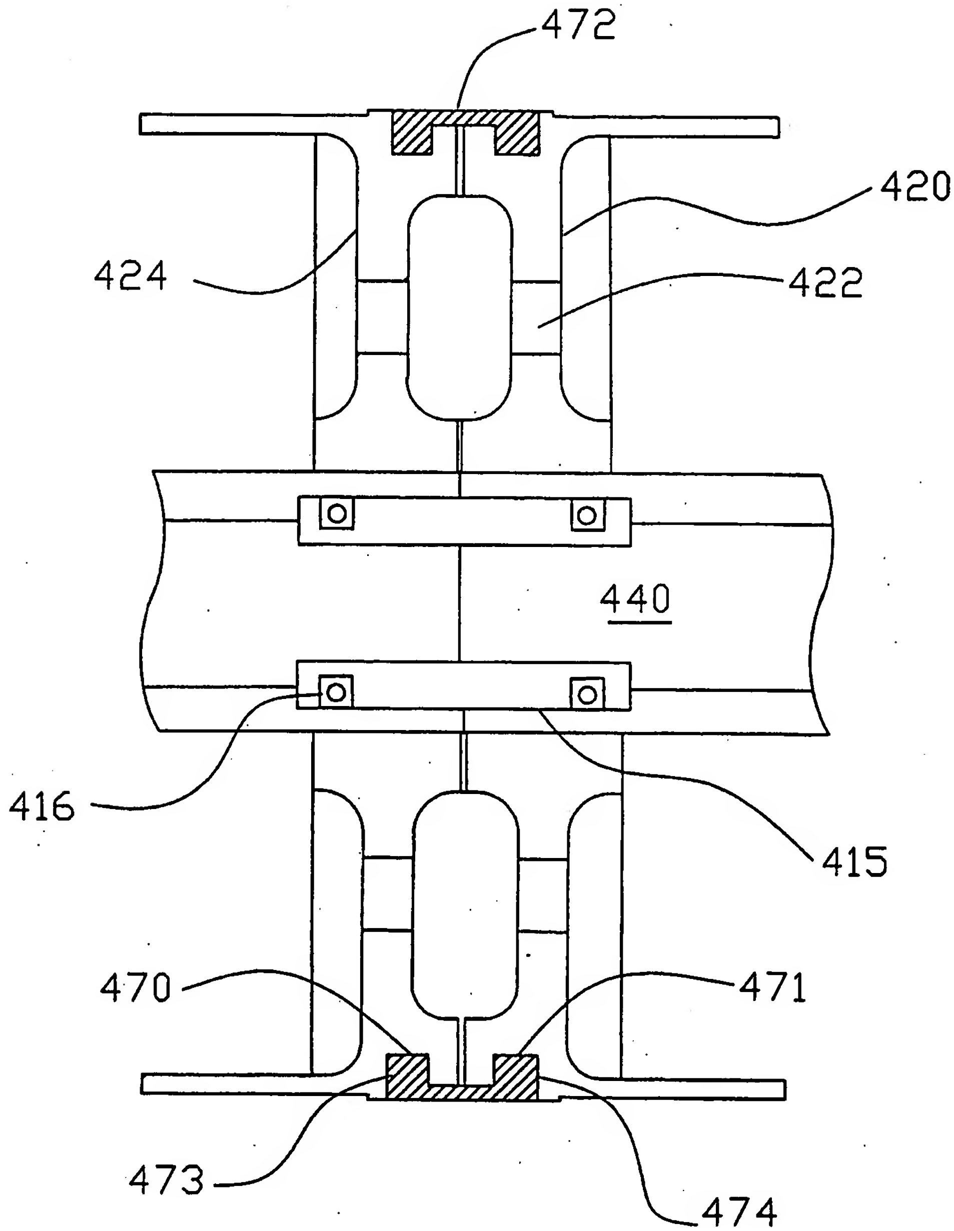


Fig. 12

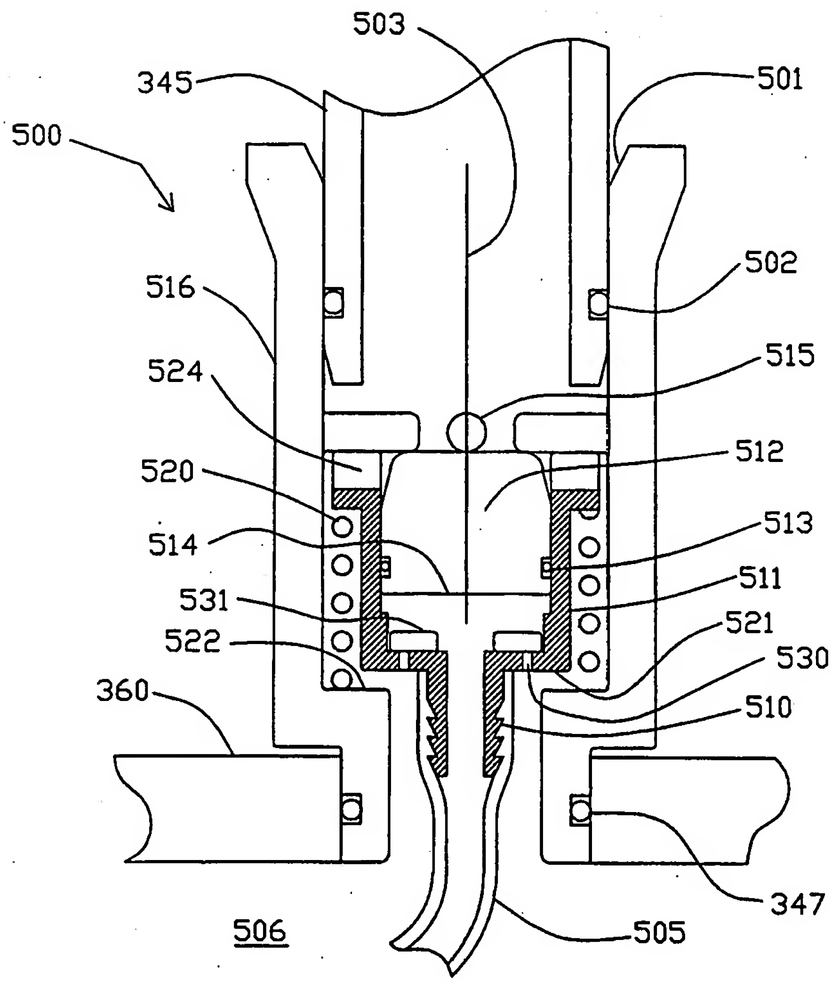

503
345
501
500
516
502
524
515
520
512
514
513
531
511
522
521
360
530
510
347
506
505

Fig. 13

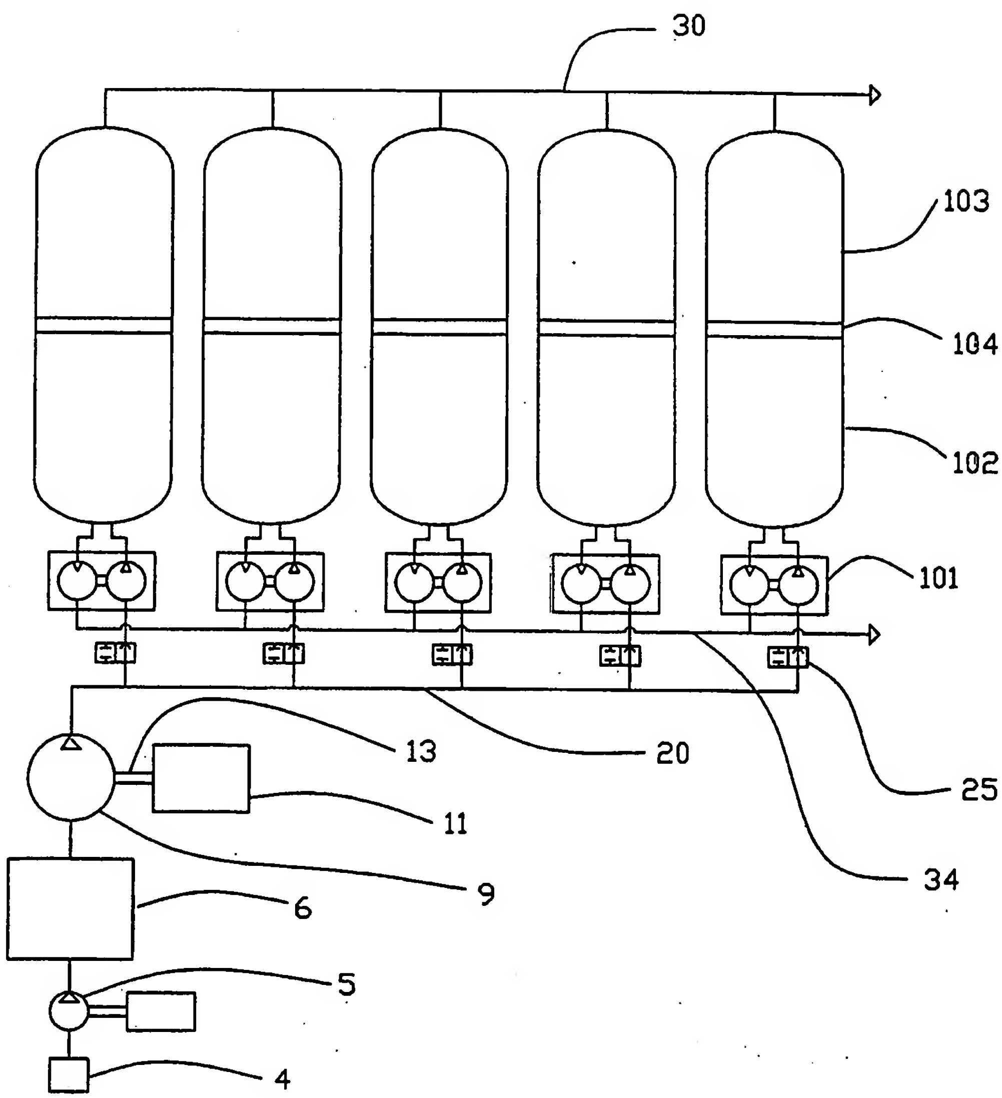


Fig. 14

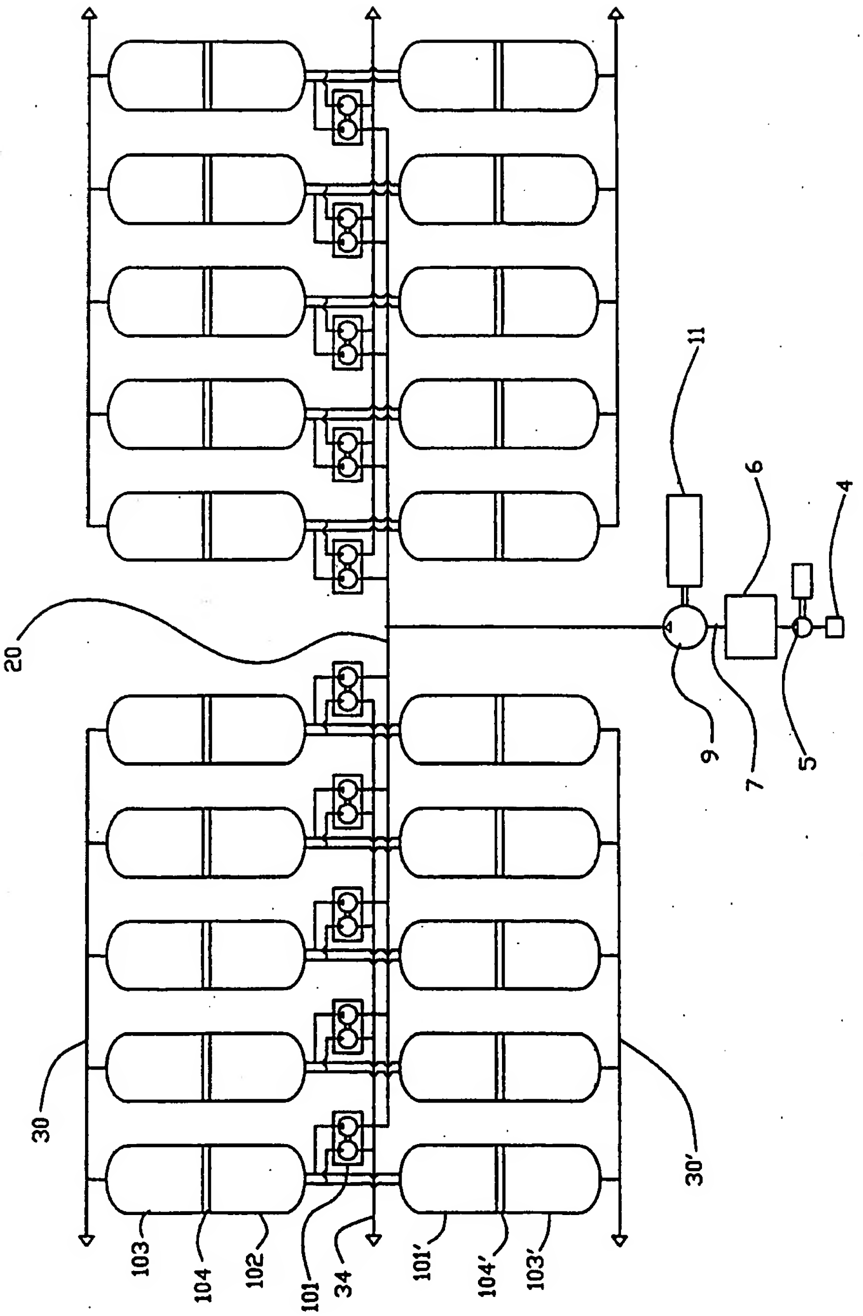


Fig. 15

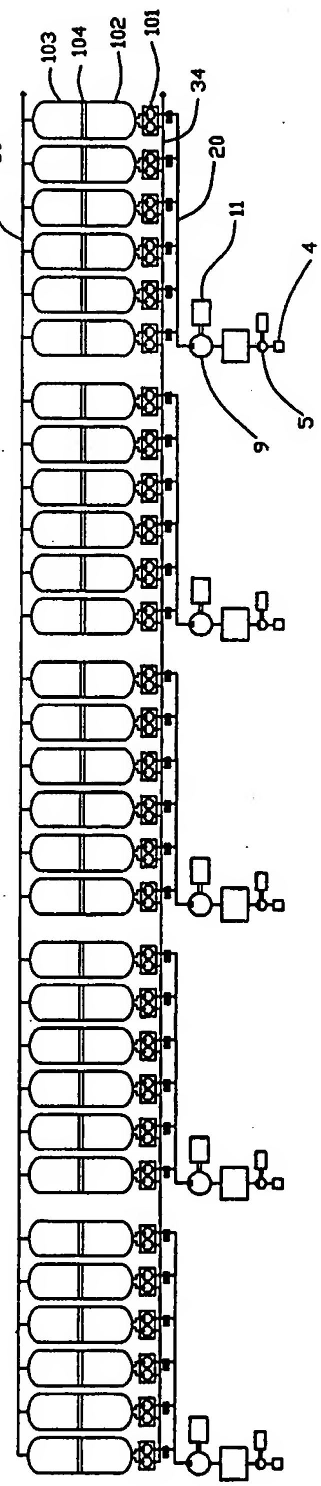


Fig. 16

INTERNATIONAL SEARCH REPORT

Interna ..al Application No
PCT/CA 97/00901

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   B01D61/06   B01D63/12   B01D61/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   B01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 207 916 A (GOHEEN DUANE F ET AL) 4 May 1993 see column 3, line 55 - column 4, line 57; figure 1 ---	1-6,10, 11,13, 15,30, 33-38
A	US 4 083 780 A (CALL NOEL STUART) 11 April 1978 cited in the application see figures ---	1,3, 10-14, 24-26, 30-34, 37,41-43
A	US 4 973 408 A (KEEFER BOWIE G) 27 November 1990 cited in the application see figures ---	1-9,30, 35-39

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
6 March 1998	27.03.98

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Persichini, C

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 97/00901

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 383 146 A (GRACE W R & CO) 22 August 1990 see figures	1,3, 10-14, 26,30, 31,33, 34,41-43
A	US 5 494 573 A (SCHOENMEYR IVAR ET AL) 27 February 1996 see claim 1	27-29

1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/CA 97/00901

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5207916 A	04-05-93	NONE	
US 4083780 A	11-04-78	NONE	
US 4973408 A	27-11-90	NONE	
EP 0383146 A	22-08-90	US 4874405 A	17-10-89
		CA 2004031 A	14-08-90
		DE 69005326 D	03-02-94
		DE 69005326 T	14-04-94
		ES 2047723 T	01-03-94
		JP 2245226 A	01-10-90
US 5494573 A	27-02-96	NONE	